USING DESIGN-BASED RESEARCH TO ANALYSE THE DEVELOPMENT OF AN INQUIRY-BASED APPROACH FOR TEACHING DIRECT CURRENT ELECTRICITY TO PRE-SERVICE TEACHERS

BY

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DECLARATION

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ABSTRACT

This study uses a design-based research (DBR) approach to develop pre-service science teachers' (PSSTs) conceptual understanding in the domain of direct current electricity. A preliminary study was conducted with a group (n=51) of PSSTs in 2010 to examine the literature, outline conceptual trajectories for the activities and assessments, and to investigate various pedagogical strategies. This was followed by a transformative conjecture-driven teaching experiment that was conducted with three cohorts of PSSTs from 2011 to 2013. The three cycles of the teaching experiment consisted of four phases each that were followed by a retrospective analysis of all the data to place it in a theoretical framework. The conjecture was advanced that an inquiry-based science teaching strategy within a social constructivist learning environment will promote the development of PSSTs conceptual understanding in the domain. Various pedagogical strategies such as science investigations, modelling, argumentation and problem-solving were adopted to help achieve this goal. Quantitative and qualitative data were collected using student assessment records and transcriptions of video data which were analysed as evidence of their conceptual understanding. The findings show that an inquiry-based science teaching approach can help to foster a better conceptual understanding of direct current electricity with varying degrees of success. The development of the students' multimodal translation skills are reasonably developed, but most lack the ability to interpret data and draw adequate conclusions. Most of the students are able to construct a physical model as evidence using principles of electricity, but not many produce appropriate arguments to explain their model. Quantitative and qualitative problem-solving is an area where the students performed poorly, except for the 2013 cohort. The findings support previous studies in the domain that students have a poor understanding of direct current and potential difference, especially as far as parallel combinations are concerned. Another important design principle to emerge is that inquiry-based science teaching strategies are not effective all the time. In such instances there is a need to complement it with traditional expository teaching strategies to develop the student's conceptual understanding of direct current electricity. The study concludes with the theories of domain-specific learning and the means to support that learning.

Key words: pre-service science teachers, design-based research, teaching experiment, inquiry-based science teaching, direct current electricity, conceptual understanding

OPSOMMING

Hierdie studie maak gebruik van 'n ontwerpgebaseerdenavorsing benadering om voordienswetenkaponderwysers se konseptuele begrip in die domein van direkte stroomelektrisiteit te ontwikkel. 'n Voorlopige studie was met 'n groep (n-51) voordienswetenkaponderwysers in 2010 aangevoer om die literatuur te ondersoek, 'n konseptuele trajek vir die aktiwiteite en assesserings te skets, en om verskillende pedagogiese strategieë te ondersoek. Dit was opgevolg met 'n transformerende vermoedegedrewe onderwyseksperiment wat met drie kohorte van voordienswetenkaponderwysers vanaf 2011 tot 2013 aangevoer was. Die drie siklusse van die onderwyseksperiment het uit vier fases elk bestaan wat deur 'n terugwerkende analise van al die data, om dit in 'n teoretiese raamwerk te plaas, opgevolg was. Die vermoede was bevorder dat 'n ondersoekgedrewe wetenskap onderrigstrategie binne 'n sosiaal konstruktivistiese leeromgewing die ontwikkeling van voordienswetenkaponderwysers se konseptuele begrip in die domein sal aanmoedig. Verskillende pedagogiese strategieë soos wetenskapondersoeke, modelle, argumentasie en probleemoplossing was aangeneem om te help om hierdie doel te verwesenlik. Kwantitatiewe en kwalitatiewe data was versamel deur studente assesseringsrekords en transkripsies van videodata, as bewyse van hulle konsonseptuele begrip, te analiseer. Die bevindings wys dat 'n ondersoekgedrewe wetenskap onderrigbenadering kan help om 'n beter konseptuele begrip van direkte stroomelektrisiteit, met 'n wisselende mate van sukses, te bevorder. Die ontwikkeling van die studente se multimodale translasie vaardighede is redelik ontwikkel, maar die meeste kort die vermoë om data te interpreteer en om voldoende gevolgtrekkings te maak. Die meeste studente kan 'n fisiese model konstruktueer as bewyse deur beginsels van elektrisiteit te gebruik, maar nie baie lewer toepaslike argumente om hulle model te verduidelik nie. Kwantitatiewe en kwalitatiewe probleemoplossing is ‘n area waar die studente sleg gevaar het, behalwe die 2013 kohort. Die bevindings ondersteun vorige studies in die domein dat studente ‘n slegte begrip van direkte stroom en potensiaalverskil het, vernaamlik sover dit parallel kombinasies aangaan. Nog ‘n belangrike ontwerpbeginsel wat na vore kom is dat ondersoekgedrewe wetenskap onderrigstrategieë nie altyd effektief is nie. In sulke gevalle is daar ‘n behoefte om dit aan te vul met traditionele verduidelikende onderrigstrategieë om die student se konseptuele begrip van direkte stroomelektrisiteit te ontwikkel. Die studie sluit af met die teorië van domeinspesifiekeleer en die wyse om die leer te ondersteun.

Sleutelwoorde: Voordienswetenkaponderwysers, ontwerpgebaseerdenavorsing, onderwyseksperiment, ondersoekgedrewe wetenskaponderrig, direkte stroomelektrisiteit, konseptuele begrip

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CHAPTER 1

INTRODUCTION

1.1 Background

Much of science teaching has been characterised by a didactic expository approach in which the transfer of facts and principles ensued through teacher-talk and the textbook as the main source of information (McBride, Bhatti, Hannan, & Feinberg, 2004: 2). This approach draws on behaviourist theory and results in children being passive receivers who respond to instructional stimuli from the teacher through drill and practice (Austin, 2013: 947). It could be compared to "a time when the science teacher presented facts to the class, and the students listened; a time when student participation in science lessons was restricted to copying notes from the board" (Mortimer & Scott, 2003: 1).

Teaching science as inquiry stands in contrast to this because it "stresses active student learning and the importance of understanding a scientific topic" as opposed to teacher-transmitted information (Chiappetta, 1997: 23). Millar and Lubben (1996: 191) stated that the central aim of science education is to help the learner acquire 'an understanding of science' which includes the following three elements:

- An understanding of some parts of the corpus of accepted science knowledge.
- An understanding of the methods and procedures of enquiry used in science.
- Some understanding of science as a social enterprise.

Duschl (2000: 188) emphasised that science education should be embedded in problem/subject contexts that afford opportunities for students to examine, discuss and engage in the epistemological, social and political bases by which scientific knowledge claims are advanced.

Franklin (2014: 1) compared the traditional didactic approach with an inquiry-based approach to science teaching as illustrated in Table 1.1 below.

	INQUIRY-BASED	TRADITIONAL
Principle Learning Theory	Constructivism	Behaviourism
Student Participation	Active	Passive
Student Involvement in Outcomes	Increased Responsibility	Decreased Responsibility
Student Role	Problem solver	Direction follower
Curriculum Goals	Process oriented	Product oriented
Teachers Role	Guide/facilitator	Director/ transmitter

Table 1.1 Comparison of the inquiry-based with the traditional approach.

Apartheid education policies in South Africa were characterised by teacher-centred teaching, rote learning, and an obsession with content and punitive formal examinations designed to achieve high levels of failure. The latter clearly falls within the traditional didactic approach. The initiative of outcomes-based education (OBE) in the late 1990s by the post-apartheid government was an effort to move towards inquiry-based teaching with constructivism as the principle learning theory. Systemic problems and a lack of resources led to a failed attempt to successfully implement OBE across the board. As a result the promise of implementing inquiry-based teaching was thwarted. Morrow (2007: 5) questioned whether OBE had actually been beneficial to the project of transforming education, whilst in fact having a profound impact on education in South Africa. He argued that it is so deeply embedded that it has become something like ‘immovable dogma’ and strongly suggested that it was offered as mere rejection of apartheid education policies.

The acquisition of skills in inquiry-based science education also helps the student to construct a better understanding of concepts. Keys and Bryan (2001: 637) argued that teachers themselves must have a deeply developed understanding of content to engage students in investigative practices. Inquiry in science education can thus be seen as a pedagogical approach that teachers employ, or it may be what students use to learn science content (Minner, Levy and Century, 2010: 476).

Sperandeo-Mineo, Fazio and Tarantino (2005: 235) posited the view that pre-service teachers[1] bring to teacher education coursework a subject matter understanding that is very different from the kind of conceptual understanding that they will need to develop in their future learners. In particular, their procedural understanding of physics is inadequate for the teaching of physics involving deep changes in content and pedagogy. If the science results in South Africa's exit examinations in Grade 12 should be a yardstick, then this is also very relevant in South Africa where there is an urgent need to address the problems in the teaching of science at high school level. It is essential that South Africa produces the next cadre of science teachers who have the necessary pedagogical content knowledge (PCK) to bring about the changes that we want and require in teaching the subject.

This study is motivated by a desire to see prospective science teachers shift from a didactic expository approach to an inquiry-based teaching approach in science education. The focus is particularly on developing the conceptual understanding of pre-service science teachers' (PSSTs) in the domain of direct current electricity through an emphasis on inquiry-based science teaching. This approach is also driven by a transformative agenda that is premised on the hope that these pedagogical strategies would ultimately be enacted in the science classrooms of these PSSTs. Howes (2002: 846) emphasised the efforts that have been made to

Note: 1. The term initial teacher education student is currently used in SA policy documents.

help students develop more authentic conceptions of scientific practice, especially where pre-service elementary science teachers were found lacking. She stressed that it is the teacher's role 'to portray science as an on-going construction of explanations of natural phenomena, developed through rules of evidence and argumentation' (ibid., p.847).

The central focus of this study is to produce a domain-specific learning environment, in particular an inquiry-based science teaching strategy for PSSTs to develop their conceptual understanding of direct current electricity. It is proposed that this can be accomplished by a *transformative conjecture-driven teaching experiment* that utilises design-based research (DBR). Figure 1.1 shows the general cyclical nature of DBR which starts with an analysis of the problem, design and development of a prototype, an evaluation which is followed by a revision. Reimann (2011: 38) posited the view that DBR is a methodological paradigm that specifies how to conduct a design study, and what gets designed is a whole learning environment with tasks, assessments and the means to sequence and scaffold the content. In essence, this is what constitutes the inquiry-based science teaching strategy.

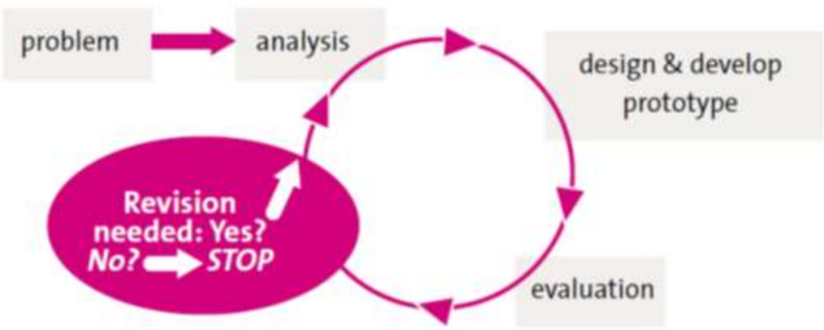


Figure 1.1 The cyclical nature of DBR (Plomp, 2013: 17)

1.2 Teacher education policy and reform efforts in South Africa

Higher education institutions in South Africa have been tasked with teacher education, which traditionally used to be shared with colleges of education. As a science teacher educator in the Bachelor of Education (B.Ed.) as well as Postgraduate Certificate of Education (PGCE) programmes at university, I am acutely aware of the need to indenture prospective science teachers into a more holistic understanding of science as praxis. Lee Shulman's (1986, 1987) notion of pedagogical content knowledge (PCK) has been key to developing this understanding. This entails developing the 'capacity of a teacher to transform the content knowledge he or she possesses into forms that are pedagogically powerful and yet adaptive to the variations in ability and background presented by students' (Shulman, 1987: 15).

In post-apartheid South Africa, reform efforts in education have been characterised by curriculum change which necessitate a broadening of the teachers' subject knowledge as well as pedagogy to improve the teaching and learning process. The extant literature on the content knowledge of South African teachers reveals that many have not mastered the curricula they are expected to teach (Spaull, 2013b: 25). Garbett (2011: 36) also argued that "teaching science effectively in primary schools is dependent upon understanding the complex relationship between learners' prior understanding, science content, teaching approaches, and pedagogical content knowledge". These views resonate with the Department of Higher Education and Training's (DHET, 2011: 53) minimum set of competences required of newly qualified teachers, one of which is that they "must be able to reflect critically, in theoretically informed ways and together with their professional community of colleagues, on their own practice in order to constantly improve it and adapt it to evolving circumstances".

The Minimum Requirements for Teacher Education Qualifications (DHET, 2011) policy document outlines various types of knowledge that teachers need in order to practise effectively. Five different types of learning are proposed for the acquisition of knowledge for teaching purposes:

- Disciplinary learning refers to subject matter knowledge.
- Pedagogical learning includes general pedagogical knowledge and pedagogical content knowledge.
- Practical learning incorporates learning in and from practice.
- Fundamental learning refers to language competence, use of technology and academic literacy.
- Situational learning refers to the various contexts and environments in which learning takes place, especially the diverse challenges in the South African context such as HIV-AIDS.

This study is set against this background of a changing education policy landscape in which there is an increasing demand for qualified, competent science teachers. The results in science and mathematics in South Africa, in particular, have been less than desirable at a national and international level such as the Trends in International Mathematics and Science Study (TIMSS). In the 2011 TIMSS South Africa's Grade 9 learners participated and completed the Grade 8 test. They demonstrated low performances (less than 400) at this level for both mathematics and science (Reddy, Prinsloo, Visser, Arends, Winnaar & Rogers, 2012: 4). However, as Spaull (2013a: 437) warns these national averages shroud the severe inequalities prevalent in

South Africa, especially in education. One way to mitigate this challenge is to shift teachers' thinking in terms of the pedagogical strategies that they employ to teach science. Traditional didactic approaches have been ineffective as it produced a docile student on the receiving end of information transfer. The proposal is to shift PSSTs to an inquiry-based science teaching approach in order to develop their conceptual understanding in the domain of direct current electricity. As stated earlier, a transformative conjecture-driven teaching experiment will be used to achieve this goal through DBR in a social constructivist setting.

1.3 Research Question

In order to be less reliant upon an algorithmic way, or simple manipulation of formulae to solve physics problems, and students being unable to offer sensible explanations for observed phenomena, the purpose of this study is embodied in the following research question:

What inquiry-based science teaching strategies will foster the development of pre-service science teachers' conceptual understanding of direct current electricity?

Sub-questions:

1.3.1 How do scientific investigations promote multimodal skills and contribute to the development of pre-service science teachers' conceptual understanding of direct current electricity?

1.3.2 How does problem-solving contribute to the development of pre-service science teachers' conceptual understanding of direct current electricity?

1.3.3 What argumentation patterns do pre-service science teachers produce to demonstrate their conceptual understanding of direct current electricity?

1.4 Methodology

Walker (2011: 52-53) indicated that design-based research has been conducted in various domains of learning, including mathematics and science education - the idea being to create a cyclic relationship between theory, research and practice. A recent South African study by Lombard (2014) also used DBR to design an artefact (strategy) to trigger introductory physics lecturers' reflections on their instructional use of representations. DBR is a flexible methodology that incorporates iterative cycles of design in real-world settings that culminates in design principles and theories (Wang & Hannafin, 2005: 6).

In this study the design cycle begins by identifying the problem, developing solutions informed by existing design principles, implementing the solutions in practice through iterative cycles, and reflecting on the principles to enhance solution implementation (Reeves, 2006: 59). DBR yields qualitative and quantitative data as is evident from the following statement:

> DBR is not a specific data collection and analysis method, but rather a framework that orients the use of other specific methods and techniques, such as video, verbal data, and statistical analysis. (Reimann, 2011: 40)

1.4.1 The transformative conjecture-driven teaching experiment

Teaching experiments within a socio-constructivist learning environment were initially one-on-one in order to understand how students learn, but evolved to classroom teaching experiments for a more productive environment (Gravemeijer & Cobb, 2013: 74). The "goal of design experiments is to develop theories about both the process of learning and the means that are designed to support that learning" (ibid., p.75). There is a need to be flexible about any conjectured learning trajectory because students' thinking and understanding might evolve in a way that necessitates a revision of pedagogical strategies.

The transformative conjecture-driven teaching experiment which is adopted in this study consists of a conjecture that has two components, namely:

a) content – what should be taught, and

b) pedagogy – how the content should be taught.

The conjecture is an inference based on incomplete evidence and the assertion is made that an inquiry-based pedagogical approach would result in PSSTs developing their conceptual understanding of direct current electricity.

The three cycles of the teaching experiment in this study was preceded by a preliminary phase which was conducted with a cohort of second-year Bachelor of Education (B. Ed.) science students (n=51) over a period of four weeks in 2010. The purpose of the preliminary phase is to outline the key concepts as well as pedagogical strategies to be adopted, and to implement assessment approaches. The B. Ed. students were enrolled for Natural Sciences in the intermediate phase (Grades 4 – 6) and senior phase (Grades 7 – 9). Most of them started their studies at university without having completed Physical Sciences at high school. This means that most of them studied Physics and Chemistry when they were in Grade 9, and then again basic introductory concepts during their first year at university.

Figure 1.2 below outlines how the teaching experiment was enacted over the different cycles of the DBR with three cohorts (2011 – 2013) of second-year science education students enrolled in a B. Ed programme at university. The preliminary phase completed during 2010 is also indicated in relation to the formal enactment of the three cycles of the teaching experiment.

	PRELIMINARY PHASE **2010 cohort (n = 51), 4 weeks**			
	• **Examine literature.** • **Outline key concepts & conceptual trajectory.** • **Outline pedagogical strategies.** • **Implement assessment strategies.**			
	Overall reflections after preliminary phase			
	CYCLE 1 **2011 (n = 63)** **6 – 7 weeks**	**CYCLE 2** **2012 (n = 60)** **6 – 7 weeks**	**CYCLE 3** **2013 (n = 47)** **6 – 7 weeks**	**RETROSPECTIVE ANALYSIS**
PHASE 1	Analysis of practical problems – literature review for conceptual underpinning	New cohort	New cohort	Retrospective analyses of the data set seek to place participants' learning and the means by which it was supported in a broad theoretical context.
PHASE 2	Development of solutions informed by the literature	Refinement of solutions based on reflection	Refinement of solution based on reflection	
PHASE 3	Intervention (first iteration) – data collection and analysis	Intervention (second iteration) – data collection and analysis	Intervention (third iteration) – data collection and analysis	The development of a domain-specific pedagogical strategy for PSSTs to develop their conceptual understanding of direct current electricity.
PHASE 4	Reflection to produce "design principles" and enhance solution implementation	Reflection to produce "design principles" and enhance solution implementation	Reflection to produce "design principles" and enhance solution implementation	

Figure 1.2 Different phases within the design cycle for various cohorts of students

1.4.2 Data collection and analysis

Each cohort of students completes a unit on direct current electricity over a period of six to seven weeks. Various inquiry-based science activities are done and some tasks have to be submitted or presented in class for assessment purposes. Table 1.2 summarises the data collection and analysis methods that are employed in this DBR study.

<table>
<tr><th>Assessment task</th><th>Format of task</th><th>Type of data</th><th colspan="2">Analysis</th></tr>
<tr><td>Scientific investigation</td><td>Practical investigation which requires manipulation of equipment, measurement and collection of data. Submission of a scientific report.</td><td>Quantitative and qualitative data.</td><td>Descriptive statistics. Process skills are analysed using Fisher's exact analysis. Students' ability to translate from one mode to another is analysed.</td><td rowspan="3">The t-test is applied to test for any statistically significant differences between the same group of students' performance on the various assessment tasks.</td></tr>
<tr><td>Project model</td><td>A working model which illustrates the basic principles of electricity is constructed in groups. The model is demonstrated to the class and the principles used must be explained.</td><td>Verbal data from video recording are transcribed.</td><td>Descriptive statistics. Qualitative data analysed for argumentation patterns and products that emerge.</td></tr>
<tr><td>Electricity test</td><td>A paper-and-pencil test which includes multiple-choice questions in which the student must provide a reason for their answer. The problem-solving type questions test understanding of concepts.</td><td>Quantitative and qualitative data.</td><td>Descriptive statistics. Understanding of concepts, reasoning patterns and process skills are analysed. Students' ability to translate from one mode to another is analysed.</td></tr>
</table>

Table 1.2 A summary of the data collection and analysis methods

1.5 Delineation and limitations

The nature of DBR is such that it takes place over an extended duration and differs from experimental research in that there are no control groups. The establishment of causal relations is therefore not the ultimate goal of DBR, but rather to outline the events and their order in what is known as "the logic of *process oriented explanations*" (Reimann, 2011: 43). This allows for the establishment of causality independently of generalisation. The effectiveness of a certain design is context-specific, but careful documentation of the events and their sequence can lead to the development of a domain-specific pedagogical strategy which can be implemented in another context.

1.6 Chaptering

Chapter 1: Introduction to the study. This chapter provides a background and motivation for the study.

Chapter 2: Literature review. The chapter outlines the philosophical framework that underpins DBR. It also shows the importance of PCK in science education and then provides the literature for inquiry-based science.

Chapter 3: Research design. This chapter focuses on DBR and the transformative conjecture-driven teaching experiment. It also considers the cycles within the design process.

Chapter 4: Design cycles. The results within each cycle are provided and an interpretation is given of each phase within the cycle.

Chapter 5: Retrospective analysis. An analysis is made to place the study within a broad theoretical context and outlines the domain-specific pedagogical strategy.

Chapter 6: Conclusion and recommendations. This chapter summarises the research findings and makes recommendations for further research.

1.7 Acronyms and abbreviations

ACT: Actual conceptual trajectory

CAPS: Curriculum Assessment Policy Statement

C2005: Curriculum 2005

DBR: Design-based research

DHET: Department of Higher Education and Training

ECT: Envisioned conceptual trajectory

MRTEQ: Minimum Requirements for Teacher Education Qualifications

NCS: National Curriculum Statement

OBE: Outcomes-based education

PCK: Pedagogical content knowledge

PSSTs: Pre-service science teachers

TIMSS: Trends in International Mathematics and Science Study

RNCS: Revised National Curriculum Statement

ZPD: Zone of proximal development

CHAPTER 2

LITERATURE REVIEW

This chapter outlines the literature that has been reviewed in developing a conceptual framework for this study. The issue of transformation in education in South Africa is sketched, followed by a discussion of pragmatism as the philosophy that underpins DBR in science education. Scientific inquiry and process skills in science are then presented as essential components to achieve the conceptual trajectories envisaged in this study. The social constructivist argument in science education provides the theoretical impetus for scientific inquiry, and the importance of PCK is highlighted. Before offering a review of research studies in the teaching and learning of basic current electricity, I outline what is meant by conceptual understanding as adopted in science education. A rationale for the choice of teaching strategies is presented followed by the pedagogical strategies that are used to develop pre-service science teachers' conceptual understanding of direct current electricity.

2.1 Transformation of education in South Africa post-1994

Education reform in post-apartheid South Africa has been characterised by major policy changes to stimulate an equitable distribution of resources, and hence a move towards equality of access for all learners. Major curriculum reform initiatives have taken place to replace the apartheid curriculum with a "new curriculum that would promote democratic principles and be relevant for a multicultural society" (Sayed & Kanjee, 2013: 15). The emergence of Curriculum 2005 (C2005) in 1997, grounded in OBE principles, heralded a shift away from ''aims and objectives" to learner outcomes with an emphasis on skills, knowledge and attitudes. C2005 was widely criticised for being overly ambitious, relied heavily on resources, and depended on poorly trained teachers for its implementation (OECD, 2008: 80). It was now expected that these same teachers, who were reared on a dose of rote learning using behaviourist pedagogy, should implement constructivist teaching approaches (ibid., p.80).

Changes to OBE were brought about based on recommendations of a ministerial committee and the Revised National Curriculum Statement (RNCS) was implemented in 2002 (Sayed & Kanjee, 2013: 18). The National Curriculum Statement (NCS) was then phased in through the grades. This culminated in the National Senior Certificate examination written by all Grade 12 learners in 2008. This represented the first time that a common examination was written by all candidates after the unification of all the different education departments. Subsequently, the NCS has been replaced by the Curriculum assessment policy Statement (CAPS) which came into effect in 2011. I concur with the sentiments expressed by Motala (2014: 286) when she commented about CAPS:

> The aim is to have a 'teacher-proof' curriculum and to ensure that learners get the fundamentals right. The outcomes-based curriculum had many flaws and was in effect unteachable in many South African schools. Nonetheless, the hope is that in reaction, exploration and discovery will not disappear completely from the new, utilitarian teaching agenda.

Carrim (2013: 49) argued that many of the debates around curriculum design and implementation had to do with educational quality on two related fronts:

- inputs as far as teacher training, support and developments are concerned, and
- outputs in terms of learner achievements.

Initially, when OBE was implemented, teachers had to rely on workshops which merely served as orientation sessions to the new curriculum. There was no real engagement with the content and pedagogy which in most instances presented a paradigm shift for the teachers.

Teachers have to implement the curriculum as a legislated imperative on the one hand, but one would hope that they are also motivated by a love for their subject/s on the other hand. However, their shortcomings alluded to earlier also served to compel the education authorities to review teacher education programmes. Teacher education programmes are being reconceptualised in the light of the Minimum Requirements for Teacher Education Qualifications (DHET, 2011) policy document which must be implemented by 2015. The policy which acquired the acronym MRTEQ "requires all teacher education programmes to address the critical challenges facing education in South Africa today – especially the poor content and conceptual knowledge found amongst teachers, as well as the legacies of apartheid, by incorporating situational and contextual elements that assist teachers in developing competences that enable them to deal with diversity and transformation" (DHET, 2011: 6-7).

Students who are enrolled in pre-service teacher education programmes such as the Post-graduate Certificate in Education (PGCE) and Bachelor of Education (B.Ed) programmes are the current generation who have to meet these challenges head-on. The aim of DBR is to bridge the gap between research and practice – it has the potential to serve as a proactive intervention which can make a real impact in the classroom. DBR is also motivated by the philosophy of pragmatism which is outlined in the next section.

2.2 Pragmatism and Science Education Research

At the heart of any research project in social science is a desire to better understand the world in which we live. The adoption of a research methodology lies in its utility value to aid this particular understanding. Pragmatists strongly advocate that the research question should drive the method and effectively call for an integration of qualitative and quantitative approaches to develop a better understanding of social phenomena (Onwuegbuzie & Leech, 2005: 377). The authors further state that "the purity of a research paradigm is a function of the extent to which the researcher is prepared to conform to its underlying assumptions" and view pragmatism as the way forward to embrace methodological pluralism (ibid., p.381). Becoming a pragmatic researcher also allows for flexibility, openness to collaboration and the ability to examine the macro as well as micro issues involved (ibid., p.383).

Pragmatism emerged from the works of Charles Peirce, William James, and John Dewey who are seen as the founding fathers of pragmatism (Biesta & Burbules, 2003: 4). Dewey's pragmatism for educational research is significant because it provides a different account of knowledge and a different understanding of the way in which human beings can acquire knowledge within a framework of a philosophy of action (ibid., p.9). The reality as experienced through the interactions between the living human organism and its environment is called transactional realism. It is deemed important rather than the dualist approach of separation of the immaterial mind and the material world (ibid., p.11). For Dewey, transactional constructivism occurs when knowledge is constructed based on the reality of the interaction. The process of creating a shared inter-subjective world is called communication (ibid., p.11).

This approach can be contrasted with the stimulus-response approach of behaviourists. The same response won't necessarily be evoked by the same environmental conditions as an individual acquires a unique set of habits over time – called prior learning (ibid., p.36). The predisposition to act is called experience and leads to learning and sense-making of the world. As Biesta & Burbules (2003: 57) aver:

> Research denotes the deliberate instigation of intelligent problem solving in order to generate knowledge and understanding.

Dewey sees no epistemological separation between the realm of theory and the realm of practice - theory does not come before practice, but emerges from and feeds back into practice (ibid., p.105).

In summary, pragmatism and its underlying transactional framework:

1. Allows for an understanding of knowledge as a function of and for human action.
2. Allows for a different way of thinking about theory and practice – specifically educational research and educational practice.
3. Sees objects of knowledge as instruments for action – different objects provide different opportunities and possibilities for action. This may influence choice of research method especially using multiple tools of inquiry to gain different perspectives of the problem at hand.
4. Looks at inter-subjectivity as a way of working together because of a shared responsibility.

(Biesta & Burbules, 2003: 107-108)

Johnson & Onwuegbuzie (2004:18) also provide a cogent summary of pragmatism:

- The project of pragmatism has been to find a middle ground between philosophical dogmatisms and skepticism.

- Rejects traditional dualisms.
- Recognizes the existence and importance of the natural or physical world.
- Knowledge is viewed as being both constructed and based on the reality of the world we experience and live in.
- Theories are viewed instrumentally (they become true and they are true to different degrees based on how well they currently work; workability is judged especially on the criteria of predictability and applicability).
- Human inquiry (i.e., what we do in our day-to-day lives as we interact with our environments) is viewed as being analogous to experimental and scientific inquiry.
- Takes an explicitly value-oriented approach to research that is derived from cultural values; specifically endorses shared values such as democracy, freedom, equality, and progress.

Juuti and Lavonen (2006:57) proposed pragmatism as a framework for design-based research in science education because they both take seriously the objective to improve praxis, especially actions as a means to acquire new knowledge to reach that objective. In this framework teaching is reflected and knowledge about science teaching and learning emerges from teaching and feeds back into teaching. They argue that cognitive modes of experience support actions and knowledge helps a teacher to better control his or her actions: i.e. to teach more intelligibly. The objective of science education research is to help teachers to act more intelligibly in the science learning environment (ibid., p.58). They concluded the following:

- A design process is essentially iterative starting from the recognition of the change of the environment of praxis,
- It generates a widely usable artifact, and
- It provides educational knowledge for more intelligible praxis. (ibid., p.65)

The philosophical perspective which is adopted in this study is pragmatism. Essentially, it is the notion of "what works" within DBR that fits in with the pragmatic stance that I find relevant. DBR seeks to design interventions at the coalface of practice using qualitative and quantitative methods. This fits in with knowledge being constructed from our experiences within the natural world. As outlined and motivated in chapter 1 of this thesis, this study is designed to shift prospective science teachers' thinking from a traditional didactic teaching approach to an inquiry-based teaching approach. The next section examines the literature in this domain.

2.3 Teaching inquiry-based science

The National Research Council (1996: 105) gave the following broad definition of scientific inquiry:

> Students at all grade levels and in every domain of science should have the opportunity to use scientific inquiry and develop the ability to think and act in ways associated with inquiry, including asking questions, planning and conducting investigations, using appropriate tools and techniques to gather data, thinking critically and logically about relationships between evidence and explanations, constructing and analysing alternative explanations, and communicating scientific arguments.

Engagement in scientific inquiry fosters an appreciation and appropriate understanding of science (Chiappetta, 1997; Haefner & Zembal-Saul, 2004). In order to "develop competence in an area of inquiry, students must have opportunities to learn with understanding" (Bransford, Brown, & Cocking, 2000: 16). When they deepen their understanding they are in a better position to transfer and apply their knowledge to different situations as they arise.

Figure 2.1 below shows the tasks associated with scientific inquiry according to Carin, Bass & Constant (2005: 21). This follows from the definition above and it indicates the interconnections between the various tasks.

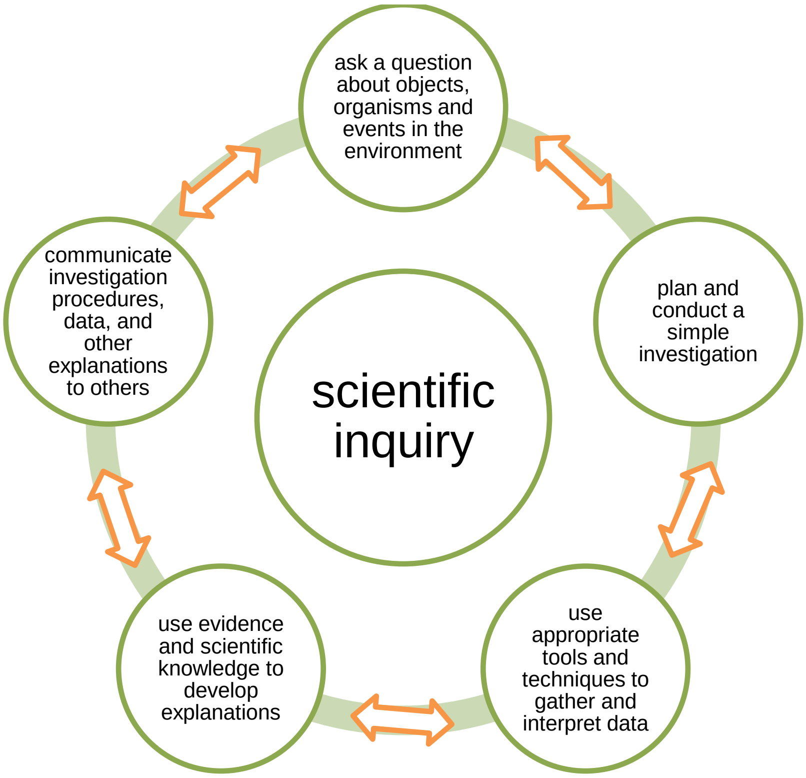


Figure 2.1 The tasks associated with scientific inquiry.

Hinrichsen, Jarrett, and Peixotto (1999: 4) undertook a literature review of science inquiry and contended that most people learn best through personal experiences and making connections to their prior knowledge. One of the primary principles of inquiry is that students must be active participants in the learning process to construct their own understanding. The authors stated that scientific inquiry centres around two big ideas:

- Inquiry as the essence of scientific enterprise, and
- Inquiry as a strategy for teaching and learning science.

Four essential and assessable traits of inquiry are highlighted:

- Students must be encouraged to discuss and explain their understanding of how a phenomenon works which should match those accepted by the science community.

- Students link concepts with science processes when they design experiments and control variables.
- Students create meaning through observations and by transforming their data to reveal relationships between variables.
- Students reflect on the meaning and interpret these relationships.

(ibid., pp. 7-8)

De Boer (2006: 19) underscored the above when he stated that scientific inquiry which involves direct hands-on investigations support the understanding of science content. Smolleck and Nordgren (2014: 15) maintained that students benefit from the ability to converse with their peers to exchange ideas and learn from one another in an inquiry science classroom. The latter point ties in with the notion of discussion as one of the traits of inquiry as stated above.

In a study conducted by Plevyak (2007: 1) she investigated how pre-service teachers' ideas about science education change over a ten- week quarter as a result of implementing an inquiry-based curriculum within a science methods course. The findings indicate that pre-service teachers' knowledge and understanding of how to implement inquiry learning deepened over the ten-week period. Varma, Volkmann and Hanuscin (2009: 15) also found in their study that when pre-service teachers' learning in a constructivist environment are integrated into the elementary science methods course, they develop an understanding of inquiry-based science instruction as well as an appreciation for the benefits of teaching and learning science through inquiry. An earlier study by Crawford (2000: 918) established that "the integration of socio-constructivist perspectives of learning with hands-on instruction enhances the opportunity for knowledge construction of inquiry". These findings are particularly relevant for this study as it involves pre-service science teachers working in a social constructivist learning environment. This is elaborated on in section 2.5 below.

Liang and Richardson (2009: 52) stated that various studies have reported the positive effects that inquiry-oriented science learning and teaching have on pre-service teachers' understanding of the nature of science, attitudes and beliefs about science learning and teaching, and their classroom teaching performance. Their study lends support to the integration of scaffolded, student-directed scientific investigations into pre-service teacher education. In a recent study conducted by Binns and Popp (2013:1) it was found, however, that pre-service teachers do not have the opportunities to practice this type of instruction during their student teaching placements. A possible explanation for this is the demand placed on teachers at these placement schools by the state curriculum as well as high stakes testing. Seung, Park and Jung (2014: 507) also concluded that although pre-service teachers had been involved in various activities designed to support their understanding of inquiry features in a science methods class, they did not implement all of the features in their actual teaching.

The concept of design-based inquiry (DBI) privileges learning through social interactions and the production of epistemic artefacts – it is premised on the idea that learning in science is best accomplished by engaging in practical activities as advocated by Dewey so many years ago (Chue & Lee, 2013: 2433). The authors highlight three advantages of DBI:

- It allows students to learn subject matter in authentic and meaningful ways.
- Students become active agents who take ownership of their own learning.

- It has a positive effect on the social aspects of learning such as collaboration and identity. (ibid., p.2434)

It is evident from the discussion on scientific inquiry that pre-service science teachers need to be exposed to this approach in order to deepen their understanding of science. Using this approach as opposed to a traditional didactic approach also implies that there are a broad range of process skills that the student must acquire to do science. The point has also been made that scientific inquiry takes place in a social constructivist learning environment that allows for interaction and engagement with hands-on science. The next section summarises the process skills needed to do science. This is followed by a literature review of constructivism in science education.

2.4 Process skills in science

Science process skills are what scientists employ when they do science, or it is the accepted conventions of scientific experimentation (Millar, 1989). They are "a set of broadly transferable abilities, appropriate to many science disciplines and reflective of the behaviour of scientists" (Padilla, 1990).

According to Martin (2011: 76) science process skills can be divided into two groups:

1. Basic processes form the foundation for scientific investigation and include the key skills such as observing, classifying, communicating, measuring, predicting and inferring.
2. The integrated processes that extend the basic processes and include identifying and controlling variables, formulating and testing hypotheses, interpreting data, defining operationally, experimenting and constructing models.

Table 2.1 summarises these two processes and provides a definition of each term according to Padilla (1990: 1-2):

Basic processes	**Integrated processes**
Observing - using the senses to gather information about an object or event. Example: Describing a pencil as yellow	*Controlling variables* - being able to identify variables that can affect an experimental outcome, keeping most constant while manipulating only the independent variable. Example: Realizing through past experiences that amount of light and water need to be controlled when testing to see how the addition of organic matter affects the growth of beans.
Inferring - making an "educated guess" about an object or event based on previously gathered data or information. Example: Saying that the person who used a pencil made a lot of mistakes because the eraser was well worn.	*Defining operationally* - stating how to measure a variable in an experiment. Example: Stating that bean growth will be measured in centimeters per week.
Measuring - using both standard and nonstandard measures and estimates to describe the dimensions of an object or event. Example: Using a meter stick to measure the length of a table in centimeters.	*Formulating hypotheses* - stating the expected outcome of an experiment. Example: The greater the amount of organic matter added to the soil, the greater the bean growth.
Communicating - using words or graphic symbols to describe an action, object or event. Example: Describing the change in height of a plant over time in writing or through a graph.	*Interpreting data* - organizing data and drawing conclusions from it. Example: Recording data from the experiment on bean growth in a data table and forming a conclusion which relates trends in the data to variables.
Classifying - grouping or ordering objects or events into categories based on properties or criteria. Example: Placing all rocks having certain grain size or hardness into one group.	*Experimenting* - being able to conduct an experiment, including asking an appropriate question, stating a hypothesis, identifying and controlling variables, operationally defining those variables, designing a "fair" experiment, conducting the experiment, and interpreting the results of the experiment. Example: The entire process of conducting the experiment on the effect of organic matter on the growth of bean plants.
Predicting - stating the outcome of a future event based on a pattern of evidence. Example: Predicting the height of a plant in two weeks' time based on a graph of its growth during the previous four weeks.	*Formulating models* - creating a mental or physical model of a process or event. Examples: The model of how the processes of evaporation and condensation interrelate in the water cycle.

Table 2.1 Two groups of science process skills.

Prediger, Gravemeijer and Confrey (2015: 880) have stated that “implicit or explicit *background theories* on teaching and learning will strongly influence both, the conception and the results of the design experiment”. It is evident from the literature on scientific inquiry that in DBR the researcher must analyse how students construct their knowledge. Constructivism as a background theory is discussed below to emphasise the orienting framework which is used for this purpose.

2.5 Constructivism in science education

> The single most important factor influencing learning is what the learner already knows. (Ausubel, 1978: iv)

The constructivist view of learning is grounded in the notion of a subjective reality and its basic ideas were proposed as long ago as 1710 by Giambattista Vico (Martin, 2011: 198). This view proposes that the only learning that can take place is that which is connected to the individual's already-existing knowledge, experiences, or conceptualisations. The teacher's job is to make sure that the learner makes his or her own connections and internalise these to construct valid meanings (ibid., p.200). The new conceptualisation will be lasting if three conditions are met:

- The new conceptualization must have explanatory power. It must provide a plausible explanation for each occurrence of the phenomenon.
- The new conceptualization must have predictive power. It must accurately predict what will happen in new and as-yet-untried occurrences of the phenomenon.
- The new conceptualization must utilize the input of others. Students discuss their ideas with each other in small groups, providing their own input and listening to others as they formulate their own notions.

(Martin, 2011: 204)

Science education discourse has been dominated by constructivism since the 1970s, and in a sense it replaced behaviourist theories of learning which were in vogue at the time. There is no doubt that the debates and contestation about constructivism have placed its protagonists and opponents on opposite sides of the fence. But, as Cakir (2008: 196) comments, “the broad, intuitive appeal that has fuelled the growth of constructivism as an epistemological commitment and instructional model may be that it includes aspects of Piagetian, Ausubelian and Vygotskian learning theories; namely, the importance of ascertaining prior knowledge, or existing cognitive frameworks, as well as the use of dissonant events (relevant information) to drive conceptual change”.

Traianou (2006: 827) contended that the effective teaching of primary science depends on the teachers’ understanding of scientific knowledge and the pedagogy necessary to teach it to children. She identifies two constructivist views comprising “small range” and “big ideas” constructivists. For the former, teachers’ adequate conceptual understanding of a small range of science concepts would suffice whereas the latter believes that broad scientific principles and the nature of a proper scientific orientation would be adequate. A sequential view of knowledge acquisition is adopted by “small range” constructivists whereby simple facts and process skills are prerequisites to higher-order forms of knowledge such as complex concepts (ibid., p.830). When situations arise that require problem-solving procedural knowledge the pedagogical repertoire of such a teacher is found lacking. On the other hand, the “big ideas” constructivist approaches the teachers’ subject knowledge by emphasising problem-solving aspects which are higher-order. They value social interaction with more knowledgeable others in the Vygotskian tradition to develop scientific understanding (ibid., p.833). Developing procedural understanding becomes essential to acquire conceptual knowledge for the primary science teacher who in turn should develop children in the same way.

Hall, Leat, Wall, Higgins and Edwards (2006: 154) argued that teachers who adopt the pragmatic Deweyan notion of learning in action will find resonance with the Vygotskian conception of learning as both socially constructed and socially supported. Garrison (1995: 717) also emphasised that a “suitable constructivist epistemology already exists deeply embedded in the tradition of Deweyan pragmatism”. The concept of scaffolding also emerged and was linked to Vygotsky’s (1978) concept of the Zone of Proximal Development (ZPD) which represents the gap between what the child could achieve alone and what is possible when guided by a more capable adult or peer. The ZPD plays an important role in designing instruction to develop conceptual understanding and it is created in the interaction between students and the teacher or in the cooperative problem-solving between peers (Liang and Gabel, 2005: 1146).

Science teaching requires a repertoire of strategies as well as its proper implementation in different classroom environments - most students have poor content knowledge and thinking skills when they enter education programmes. Application of Vygotsky’s social constructivism during the learning process can help negotiate the conceptual trajectory that must be traversed. Liang and Gabel (2005: 1159) found in their study that students lacked the intellectual persistence for in-depth exploration and coherent conceptual development. They proposed teacher-guided discussion and argumentation for the students to achieve higher levels of reasoning and conceptual understanding.

Hyslop-Magison and Strobel (2008: 76) also suggested that knowledge is socially rather than individually constructed. They cite the example of the fact that smoking causes cancer as having been established by experts in the field and not the individual's own cognitive structures. Social constructivism "espouses the view that knowledge is a cultural or negotiated artefact generated in cooperation and understanding with others" which can be attained through guided instruction (ibid., p.81). These tie in with the notion of a conceptual trajectory which can be mapped for the student in a certain content domain to acquire conceptual knowledge. The authors argued that Dewey's constructivist objective of empowering the individual learner can be complemented by Vygotsky's social constructivism. The constructivist learning environment which applies these practices designs activities that are transformative and sets high learning demands to challenge the learner during problem-solving. Hyslop-Magison and Strobel (2008: 84-85) further advocated that prospective teachers must add constructivism's insights and pedagogical implications to their teaching repertoire. This leads to an awareness of students' preconceived notions that serve as an impediment to develop new conceptual understandings.

Kruckeberg (2006: 2) argued that Dewey's thinking seems congruent with constructivist thinking where learning something new depends on the experience and knowledge one already has. To think of science as a means for making connections in experience could be thought of as Deweyan constructivism. The author proposed that we learn scientific ideas in the Deweyan sense because:

- They are products of a kind of investigative interaction that involves conscious deliberation in projecting, testing, and constructing ideas within a community of inquirers in order to solve practical problems.

- They are relational concepts that serve to connect a broad scope of ideas in a way that points to possible future interactions. (ibid., p.25)

Johnston (2009: 25) reasoned that Deweyan inquiry in science education involves active experimentation, collection of data, formation of hypotheses, etc. Dewey recommended a practical approach to science education in which the materials that are manipulated have a connection outside the classroom or laboratory (ibid., p.35).

Taber (2011a: 258) also maintained that constructivism has been prominent in science teaching and science education research since the late 1970s. This has seen teaching being conceptualised in terms of a shift from where the learner's thinking is to where we would like it to be – much like scaffolding in the ZPD.

The modern constructivist perspective "assumes that the learner comes to knowledge by recognising the meaning of what is found in the environment" (Taber, 2011b: 41-42). The aim of teaching is to foster understanding of phenomena, but meaningful learning cannot take place by rote learning which has its place in certain instances. The learner could give a verbatim definition of say Newton's second law of motion, but still lack the ability to apply the law to a problem to demonstrate understanding. According to Taber (2011b: 44) the individual has to construct a meaningful interpretation of his experiences in the environment through a process of personal meaning making. This resonates strongly with the pragmatic tradition of John Dewey.

Learners are often confronted by abstract concepts in science so the teacher must guide the learning process by adopting appropriate pedagogical strategies. This connects again to the Vygotskian notion of scaffolding in the ZPD. The individual exists within a social and cultural context where they construct their conceptual frameworks through interactions with others (ibid., p.50). Taber raises the question of what approaches to pedagogy might be considered to be constructivist. ‘Discovery’ learning could be supported by constructivist teaching if the activities are carefully designed to scaffold the desired learning (ibid., p.56). On the other hand, inquiry learning has a primary rationale of teaching students the skills and processes of inquiry such as data collection, analysis, argumentation, etc. Constructivist inquiry teaching will guide the student in the methods of inquiry so that they work within their ZPD. Constructivist pedagogy thus entails both student-centred and teacher-directed mediation to ensure optimum levels of teaching.

Murphy (1997:11-12) outlined the characteristics of constructivist teaching and learning which could be used to identify its prevalence in the classroom. Some of the more salient features which apply to this study are:

1. Multiple perspectives and representations of concepts and content are presented and encouraged;

2. Teachers serve in the role of guides, monitors, coaches, tutors and facilitators;

3. The student plays a central role in mediating and controlling learning;
4. Knowledge construction and not reproduction is emphasised;
5. This construction takes place in individual contexts and through social negotiation, collaboration and experience;
6. The learner's previous knowledge constructions, beliefs and attitudes are considered in the knowledge construction process;
7. Problem-solving, higher-order thinking skills and deep understanding are emphasised;
8. Knowledge complexity is reflected in an emphasis on conceptual interrelatedness and interdisciplinary learning;
9. Collaborative and cooperative learning are favoured in order to expose the learner to alternative viewpoints.
10. Scaffolding is facilitated to help students perform just beyond the limits of their ability.
11. Assessment is authentic and interwoven with teaching.

My own approach to science teaching has been influenced by my undergraduate years in physics and chemistry where laboratory sessions complemented the theoretical components of the course. This was enhanced during science methods classes during my induction to teaching. As a novice high school Physical Sciences teacher I borrowed equipment from the science education unit at university if my school did not have the necessary laboratory apparatus. Whilst the practical sessions at school were constrained by a lack of equipment, it necessitated a need to allow learners to work collaboratively to complete their investigations. This approach to teaching and learning in science is supported by the Vygotskian notion of knowledge being socially constructed.

I have shown that Dewey's pragmatic approach to science education, whereby the student interprets his experiences in the environment, has elements of social constructivism embedded within it (Garrison, 1995; Hall et al., 2006; Kruckeberg, 2006). Thus, my approach to science teaching is that of a "big ideas" constructivist who promotes higher-order thinking skills in the students' ZPD through interaction with his peers and teacher in the social environment.

Prediger, et al. (2015: 881 - 882) have shown that a set of three broad assumptions about learning are derived and used by design researchers from these foundational thinkers such as Dewey and Vygotsky. These are:

- Students are treated as epistemic agents who bring to bear their own experience and resources.
- Design research with this background is typically conducted over an extended time period as students learn substantial ideas, conceptions, or strategies.
- Design researchers have to closely attend to the discourse in the studied classrooms.

This requires careful documentation and the students' work form an important part of the design study as it is used as evidence in the learning process.

In science teacher education, the development of the prospective teacher's PCK is fundamental to fostering an understanding of content, and to provide exposure to pedagogical strategies. This important concept is discussed next.

2.6 Constructing pedagogical content knowledge in science

In an interview conducted by Berry, Loughran and van Driel (2008:1275-1276), Lee Shulman had the following to say about American elementary school teacher trainees:

> "…a teacher who does not both understand and have a real affection for a subject will never be able to teach it well. … so many elementary teachers model a kind of math anxiety… one of the consequences of weak subject matter preparation and a sense that one is weak in it, is that it leads to rigid pedagogy … Pedagogy that is highly didactic …"

These views espoused by Shulman could well be juxtaposed with the Bachelor of Education teacher education programmes in South Africa. Pre-service mathematics and science teachers at the primary school level generally do not follow undergraduate courses in these disciplines offered within Natural Sciences faculties. The challenge facing education faculties is how best to merge content with pedagogy given the poor preparation of students entering university. In the light of the aims of this study which is to move students away from a traditional didactic approach, this rigidity Shulman alludes to could well be a challenge in physics.

Lee Shulman introduced the concept of pedagogical content knowledge (PCK) as a theoretical construct that describes the 'particular form of content knowledge that embodies the aspects of content most germane to its teachability' and that comprises 'the ways of representing and formulating the subject that make it comprehensible to others' (Loughran, Mulhall and Berry, 2008: 1301-1302). PCK is thought to be an amalgam of a teacher's pedagogy and understanding of content such that it influences their teaching in ways that will best engender students' learning for understanding (Berry et al., 2008: 1272). Teacher education programmes have not focused on PCK per se except perhaps its theoretical aspects while advocating the attainment of PCK by pre-service teachers as a goal or outcome for the programme (Loughran et al., 2008: 1301). Its usefulness in the microteaching and teaching practice situation for pre-service teachers has not been fully explored.

Loughran et al. (2008: 1302-1303) used PCK as a conceptual framework to study how pre-service teachers might better structure and understand what it means to learn to teach science and how that learning might influence their understanding of the nature of science teachers' professional knowledge. The authors concluded that by being sensitised to the notion of PCK, the participants in the study attempted to better align the content matter with pedagogy. They suggest that pre-service teachers have come to see PCK not so much as an educational theory but as a way of looking into how they might develop their own professional knowledge of practice (ibid., p.1317).

Rollnick, Bennett, Rhemtula, Dharsey and Ndlovu (2008: 1365) presented two South African case studies designed to explore the influence of subject matter knowledge on pedagogical content knowledge. In the first case study on teaching the mole concept in two township schools, the findings illustrate that the participant teachers favoured procedural approaches at the expense of conceptual understanding. The second case study examines the teaching of chemical equilibrium to students on a bridging programme in a tertiary institution. The study has shown that strategies emphasising procedural approaches may be as much a product of contextual factors (demands of external examinations, inadequate student backgrounds, and impoverished classroom environments) as of teachers' limited content knowledge (ibid., p.1383). The relevance of these findings to this study, albeit in physics education, is that these traditional didactic approaches come at the expense of developing conceptual understanding when rigid procedures are followed.

Nilsson (2008: 1282) examined how student teachers' understanding of practice might be mapped and conceptualized by looking at aspects of the development of their PCK. In a transformative process to develop the amalgam (PCK), they might come to recognise and understand the complexity of teaching and see value in transforming their knowledge into a form that is useable and helpful in shaping their classroom teaching of science (Nilsson, 2008: 1282). Four student-teachers, who taught physics to students aged 9–11 years once a week over the course of a year, were studied in pairs. The topics included electricity, heat and temperature, optics, sound, and mechanics. Through collaboration and structured reflection on their teaching experiences, their understandings of subject matter knowledge (SMK), pedagogical knowledge (PK), and contextual knowledge (CK) were examined. The author concludes that creating possibilities for pre-service teachers to recognize that learning about teaching also comprises the development of the sophisticated knowledge of practice that is PCK requires real possibilities for them to build on the dynamic interplay between (at least) SMK, PK, and CK through their practice.

Lowery (2002: 68) undertook a study to determine how pre-service teachers construct teacher knowledge and PCK of elementary mathematics and science in a school-based setting using a constructivist instructional approach. The findings confirmed the acquisition of teacher knowledge and PCK through scaffolded learning experiences in a situated context of school. In contrast, Irving, Dickson and Keyser

(1999) designed unique professional development courses for secondary science teachers that integrated content with pedagogy. Their findings showed that teachers improved their command of science subject matter and pedagogical skills necessary to create constructivist learning environments.

There is no universally accepted definition or conceptualization of PCK. Gess-Newsome (1999a: 10–13) described two models, the Integrative Model and the Transformative Model. In the Integrative Model (figure 2.2), teacher knowledge is explained as an intersection of subject matter, pedagogy, and context. Knowledge from all three domains is integrated as needed to create effective learning opportunities. The advantage of an Integrative Model is that domains of knowledge can be developed independently and be integrated at a later stage. A potential danger with the Integrative Model is that teachers may never see the importance of such knowledge integration and emphasize content over pedagogy which results in transmission modes of teaching.

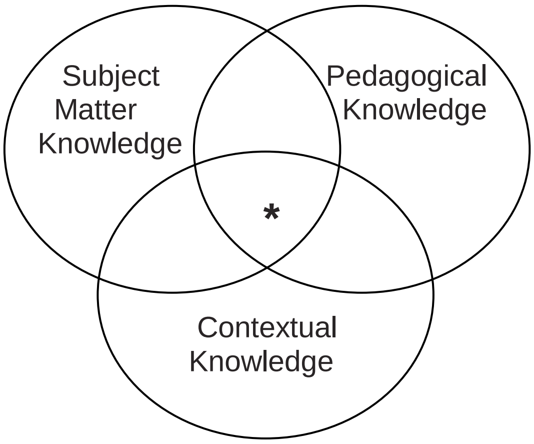


Figure 2.2 The integrative model of PCK
***** = knowledge needed for classroom teaching

The Transformative Model (figure 2.3) represents a synthesis of all knowledge. Knowledge of subject matter, pedagogy, and context, whether developed separately or integratively, are transformed into PCK. Teaching knowledge is contextually bound, making it difficult to transfer, which implies that appropriate teaching practices are needed for a particular context. A danger with this model is that it could be seen as objectifying teaching so that the development of teachers' decision-making skills, personal growth, and creativity might be overlooked (Nilsson, 2008: 1283).

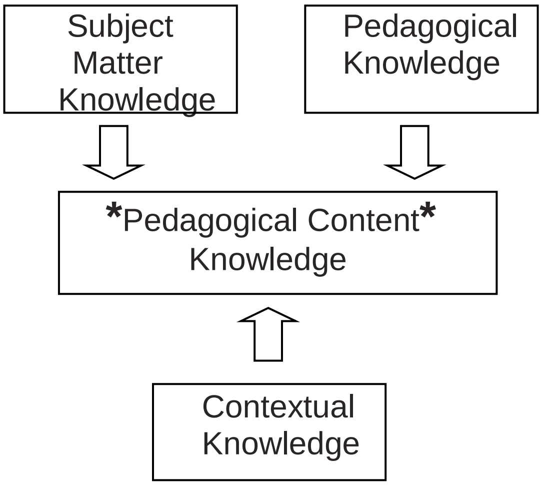


Figure 2.3. The transformative model of PCK
***** = knowledge needed for classroom teaching

Gess-Newsome (1999b: 63) contended that pre-service teachers do not have the conceptual understanding of the content that they are supposed to teach and their subject matter knowledge is 'fragmented, compartmentalized, and poorly organised'. Many novice teachers thus resort to teaching algorithms and facts that they remember from their own school days which in turn limit conceptual understanding and learning opportunities.

Loughran, Milroy, Berry, Gunstone and Mulhall (2001: 289) developed an approach to articulate and portray science teachers' PCK based on what they call the CoRe (Content Representation) – which represents the particular content/topic of the science teaching – and PaP-eRs (Pedagogical and Professional experience Repertoire) – which help to illuminate specific aspects of the CoRe and therefore offer insights into PCK. The CoRe and PaP-eRs represent an attempt to make the tacit knowledge of experienced science teachers explicit to others. What emerged is a clear debunking of the notion that a standard exemplar of PCK can be used as a yardstick in all contexts.

Halim and Meerah (2002: 215) examined 12 trainee Malaysian science teachers' PCK of selected physics concepts. The participants were interviewed on selected basic concepts in physics that are found in the Malaysian Integrated Science curriculum for lower secondary level. The findings showed that trainee teachers' PCK for promoting conceptual understanding is limited as they were unable to transform their understanding of basic concepts in physics. Their level of content knowledge affected their awareness of pupils' likely misconceptions. As a result the trainees were unable to employ the appropriate teaching strategies required to explain the scientific ideas.

The dilemma that confronts teacher educators in initial teacher education programmes in South Africa, and internationally for that matter as gleaned from the literature, is how best to balance content and pedagogy. This is uniquely captured in the notion of PCK as conceptualized by Shulman. It is concerned with how content is imparted so as to engender conceptual understanding of a particular concept or in a particular discipline. The teaching experiment which is adopted in this study has the distinctive component features of content and pedagogy. This is expanded on in

Chapter 3 of this thesis. In the next section I examine the notion of conceptual understanding in science education.

2.7 Towards conceptual understanding in science education

Taber (2013: 122) argued that research on student understanding must be clear about what is being researched. Is the understanding to be judged against an external norm, or is it something to be characterised on an individual basis? He distinguishes between a *normative-positivist* approach and an *idiographic* approach which he summarised as illustrated in Table 2.2 below:

Approach	**Normative-positivistic**	**Idiographic**
Ontological assumption	Understanding can be judged as right or wrong/ present or not	Understanding is complex and holistic, consisting of a rich array of interlinked elements
Epistemological assumption	Student understanding of a science concept can be operationalized to produce simple statements which can be objectively compared between individuals or against specified targets for learning	Student understanding of a science concept area needs to be explored through in-depth probing using qualitative methods capable of uncovering nuances of meaning
Methodological consequences	Research starts with an analysis of target understanding, and the identification of key elements against which understanding is to be evaluated.	Research involves detailed exploration of the way the individual student understands the target concept/topic

Table 2.2 Comparison of two ways of understanding, taken from Taber (2013: 124).

In practice there appears to be a linking of the two approaches. For example, a detailed description of student understanding could be given, but yet it could be compared with the norm prevalent for the same age-group of students (ibid., p.136). Hewitt (1983: 309) made the following point about conceptual understanding in physics:

> " … I'm arguing there is also another essential to be considered. And that essential *is* missing in physics instruction. That essential is conceptual understanding of basic physics – the ability to conjure up a mental image of a physics interaction, process, or concept and to be able to describe it verbally and symbolically and to be able to distinguish the concept from others that are closely related".

This quote ties in with the focus of this study which is to develop PSSTs conceptual understanding of direct current electricity by adopting an inquiry-based science teaching strategy. In particular, it is the qualitative description and multimodal representation of the concept that is an ultimate goal to develop understanding. From a students' perspective any discussion in physics which is devoid of any formulae to solve problems is not important. Students have been routinely exposed to an excess of formulae and algorithms to do problem-solving. When they are required to explain the same phenomena they are often unable to do so in a coherent manner. Sadler (2006: 324) argued for the inclusion of discursive practices in science education programmes that promote student understanding of the scientific enterprise and the portrayal of scientific knowledge as socially constructed. These recommendations have serious implications for the pedagogy of science teachers.

While The Trends in Mathematics and Science Study (Mullis, et al., 2003) has been cited extensively to show South Africa's poor performance in these subjects, the three broad cognitive domains that are assessed during the study are useful. These are:

1. Factual Knowledge
2. Conceptual Understanding
3. Reasoning and Analysis.

Conceptual understanding in science means having a grasp of the relationships that explain the behaviour of the physical world and relating the observable to more abstract or more general scientific concepts (Mullis, et al., 2003: 64). As students progress through school, the level of complexity of conceptual understanding increases and it cannot be measured directly. The study includes quantitative problems requiring a numerical solution and qualitative problems requiring a written descriptive response. Students should be able to use models to illustrate structures and relationships and demonstrate knowledge of scientific concepts when they give an explanation. Table 2.3 illustrates the skills students need to demonstrate conceptual understanding in science.

Illustrate with Examples	Support or clarify statements of facts/concepts with appropriate examples; identify or provide specific examples to illustrate knowledge of general concepts.
Compare/Contrast/Classify	Identify or describe similarities and differences between groups of organisms, materials, or processes; distinguish, classify, or order individual objects, materials, organisms, and processes based on characteristics and properties.
Represent/Model	Use/draw diagrams and/or models to demonstrate understanding of science concepts, structures, relationships, processes, and biological/physical systems and cycles (e.g., food webs, electrical circuits, water cycle, solar system, atomic structure).
Relate	Relate knowledge of underlying biological and physical concepts to the observed or inferred properties/ behaviours/uses of objects, organisms, and materials.
Extract/Apply Information	Identify/extract/apply relevant textual, tabular, or graphical information in light of science concepts/principles.
Find Solutions	Identify/use science relationships, equations, and formulas to find qualitative or quantitative solutions involving the direct application/demonstration of concepts.
Explain	Provide or identify reasons/explanations for observations or natural phenomena, demonstrating understanding of the underlying science concept, principle, law, or theory.

Table 2.3 Skills students need to demonstrate conceptual understanding (Mullis, et. al., 2003:64-65)

During assessment opportunities to test student understanding in this study a range of these skills will be tested. Students have to build a model and explain how it works to illustrate principles in direct current electricity. They must also interpret information in different modes, and they must be able to solve electric circuit problems in a quantitative and qualitative manner. The next section outlines the research that has been conducted in direct current electricity.

2.8 Research on the teaching and learning of electricity

Before presenting the research studies on the teaching and learning of direct current electricity, it is appropriate to summarise research into the teaching and learning of physics in general. Bernhard and Carstensen (2002: 2) summarised the findings as follows:

- Functional understanding cannot be accomplished by quantitative problem-solving alone - questions must elicit qualitative understanding.
- A coherent conceptual framework is not typically an outcome of traditional instruction. Rote use of formulae is common.
- Traditional instruction does not promote conceptual understanding. Other means must be used in different contexts to overcome difficulties.
- Scientific reasoning skills must be cultivated since traditional instruction does not help to achieve it.
- Connections among concepts, formal representations, and the real world are often lacking after traditional instruction.
- Teaching by telling is an ineffective mode of instruction for most students. Student understanding could be enhanced by promoting critical thinking skills.

While examining the literature on research that has been conducted on the teaching and learning of electricity, it became evident that extensive reference was made to earlier innovative studies, which it rightly should. It would therefore seem logical to present these studies in a chronological order and not the latest research studies first. There is, however, a common denominator – student understanding of key concepts in electricity remains problematic and their misconceptions are as pervasive as ever. Duit and von Rhöneck (1997: 50 - 52) made the following general comments about students' understanding about current, voltage and resistance across age groups and education levels:

- The term current has a wide spectrum of meanings in everyday use that teachers need to be aware of.
- The notion that current is consumed in the light bulb is pervasive and does not disappear with formal teaching.
- Students employ local reasoning by focusing on one point in a circuit regardless of the rest of the circuit.
- Students fail to differentiate between voltage and current.
- Students use sequential reasoning by considering a "before" and "after" current "passes" a point.
- The concept of resistance is also problematic as incorrect reasoning is applied in a circuit.

Cohen, Eylon and Ganiel (1983: 407) administered a diagnostic questionnaire to a sample of high school learners (n=145) and physics teachers (n=21) and examined the way in which they understood the functional relationships between the variables in an electric circuit. How they conceptualised the relative roles of potential difference and current and how this affects the way in which they analysed simple circuits was the main focus of the study. It was found that they emphasised current rather than potential difference which could possibly be ascribed to a lack of clarity in the curriculum regarding the causal relation between the two, as well as the order of presentation of the two concepts. Students are also unable to consider what effect changing one variable has on the rest of the circuit, and they resort to algorithms when confronted with questions probing their understanding (ibid., pp. 411-412).

Shipstone, von Rhöneck, Jung, Kärrqvist, Dupin, Johsua and Licht (1988: 303) described a study of the understanding of basic electrical concepts shown by 15-17 year-old students in England, France, The Netherlands, Sweden and West Germany. The same objective test was administered to samples of students in each of these countries. Significant differences were found on certain concepts: one concerned with current and the flow of charge and energy, and the other with voltage and its relationship to current.

McDermott and Shaffer (1992: 994) from the Physics Education Research Group at the University of Washington (PERG-UW) examined student difficulties in various domains of physics and subsequently designed instructional strategies to address those difficulties. They highlighted the fact that serious misconceptions exist about electric circuits and that the ability to solve quantitative problems does not guarantee conceptual understanding – students are unable to answer qualitative questions on the same physical concepts. Students in the study came from backgrounds ranging from no prior formal study in physics to those with a major in the subject. Prospective and practising teachers were also involved. It was found that three categories of difficulty emerged, but they are not mutually exclusive: an inability to apply formal concepts to electric circuits, an inability to use and interpret formal representations (e.g. diagrams, graphs and equations) of an electric circuit, and an inability to reason qualitatively about the behaviour of an electric circuit (ibid., p.995). Students had to explain their answers in an interview so that the design of the instructional strategy is directed at the underlying faulty reasoning. The authors concluded that serious conceptual and reasoning difficulties remained even after the presentation of material in the traditional lecture and laboratory format (ibid., p.1002). They recommend that the development of the curriculum must be based on research of what the students know and are able to do rather than an assumption of what they are supposed to know and do.

In a follow-up article, Shaffer and McDermott (1992: 1003) described the application of the results of the research to develop specific strategies and the continuous evaluation of the materials based on classroom experience. They concluded that students thought of the concepts of current, potential difference and resistance primarily as variables in an algebraic formula and recommended that on-going systematic investigations be carried out into the nature of student difficulties. In building up a research base it is important to record not only what methods work, but also which ones do not work (ibid., p.1012).

McDermott,Shaffer and Constantinou (2000: 412) argued that teachers “should be able to do the qualitative and quantitative reasoning that underlie the development and application of concepts”. Courses in Physics education should not focus on mathematical manipulation, but rather qualitative reasoning. There should be practical opportunities to develop an understanding of concepts by observing, making inferences and drawing conclusions. To prepare teachers to teach electricity by inquiry, a qualitative model was used to predict and explain the behaviour of simple circuits. For example, they build a model to try and light a bulb using a single wire and battery. This develops the notion of a complete circuit which is then applied to other more detailed circuits. During assessment the teachers showed an improved understanding when they had to reason qualitatively when substantiating an answer to a multiple-choice question.

Mulhall, McKittrick and Gunstone (2001: 576) have shown that there has been a strong emphasis on research in the teaching and learning of electricity. The reasons forwarded are that electricity in some form is seen as a central area of physics / science curricula at all levels of education, and the concepts of electricity are highly abstract and complex. Student understanding remains resistant to change after teaching, but their ability to do algorithmic problem-solving is often enhanced. A didactic exposition of the content is common whereas learners' minds need to be actively engaged (ibid., p.577). The two central questions that the authors tried to answer in their research are: (a) what range of models/analogies/metaphors are appropriate in the teaching/learning of electricity at different levels of education, including what justifications there are for each model etc. and its use at a particular level; (b) what, in detail, do we expect students to learn when we talk of "conceptual understanding" in electricity, and how might this change with level of education (or, what are justifiable forms of concepts such as resistance, potential difference at different levels). They concluded that no clear answers emerged, unlike with a concept such as the particulate nature of matter where there is agreement in terms of the models/analogies/metaphors and conceptual learning outcomes (ibid., p.583).

Ates (2005: 213) undertook a study to explore the effectiveness of the learning-cycle method as opposed to the traditional instructional method when teaching direct current circuits to university students. The learning-cycle group significantly outperformed the traditional group in understanding key concepts. Reasons that are offered include students' exposure to hands-on activities that stimulate them to think and argue about their prior conceptions lead to the construction of better conceptions (ibid., p.223).

Küçüközer and Kocakülah (2007:101) conducted a study to reveal secondary school students' misconceptions about simple electric circuits and to define whether specific misconceptions peculiar to Turkish students exist within those identified. The findings show that the misconceptions which emphasized the idea of "no bulb lights on if the switch is off" due to everyday language, and the idea of "bulbs connected in parallel give better light than those connected in series" due to prior teachings were peculiar to Turkish students. Other findings corresponded to those found in the literature such as "batteries are constant current sources" and "consumption of the current by circuit components". The authors suggest that curriculum planners take these misconceptions into account when designing materials.

Shen, Gibbons, Wiegers and McMahon (2007: 435) conducted a course to prepare teachers to conduct inquiry-learning which focused on hands-on activities and observations and constructing scientific models in current electricity. They used research-based assessment tools to identify teachers' mental models and concluded that it “is a promising way to use the knowledge of alternative conceptions in science education” (ibid., p.437). In addition, formative assessment is used to help learning as the teachers create scientific models in discussion with their peers.

Küçüközer and Demirci (2008:303) conducted a study to determine pre-service (n=32) and high school (n=25) physics teachers’ ideas about simple electric circuits. Eight questions were given to them to complete and it was found that the pre-service physics teachers had alternative conceptions on seven out of the eight questions while the high school physics teachers had alternative conceptions on four of the questions. The authors recommend that teacher educators pay attention to more hands-on experiences and move in the direction of evidence-based practice (ibid., p.308).

Gunstone, Mulhall and McKittrick (2009: 515) conducted interviews with a number of experienced senior high school physics teachers to explore their perceptions of difficulties in student learning and their own teaching of direct current (DC) electricity. Their use of models and analogies in teaching, and their own understandings of the concepts of DC electricity were also explored. The authors posit the view that the understanding of DC electricity by learners of all ages before any formal learning experiences is highly idiosyncratic, strongly influenced by everyday uses of words such as: “power”, “flow”, and, especially, “voltage”, very commonly in conflict with the conceptions of physics, and frequently little changed by conventional teaching sequences (ibid., p.516). They found the levels of conceptual understanding of the concepts of DC electricity of some teachers of particular concern and conclude that these inadequacies and epistemological uncertainties are most likely the consequence of the content and quality of undergraduate physics teaching (ibid., p.531).

Afra, Osta and Zoubeir (2009:103) investigated the alternative conceptions that a group of 12 Lebanese students in a grade 9 class hold about electricity. They also attempted to evaluate the learning outcomes of implementing in that class an inquiry-based module for the acquisition of conceptual understanding of basic concepts in electricity. Afra et al. (2009:104-105) provide a pertinent overview of the conceptual models that students adopt: the *unipolar* model, whose adopters don't recognise the need for a closed circuit, and therefore treat electric components as *electric sinks* that transform the current sent by a battery into light and/or heat; the *attenuation* model, whereby the current leaving a battery from one end is 'used-up' by the elements in the circuit, and the unused portion returns back to the other terminal of the battery; and the *sharing* model, where the current sent by a battery is split and shared among the different components in the circuit. Potential difference is also not seen as the cause of the current and many students fail to develop an understanding of resistance. Research studies also show that students have poor reasoning ability and that inquiry-based teaching sequences foster conceptual understanding. In this study it was found that most of the alternative conceptions and conceptual difficulties outlined above existed amongst the participants.

Kock, Taconis, Bolhuis and Gravemeijer (2013: 579) designed a sequence of instructional activities and a conjectured learning process in simple electric circuits with high school students. While they initially set out to develop a local instructional theory to develop the students' conceptual understanding, this changed to understanding the inherent characteristics of inquiry-based teaching that complicate the process. This occurred during retrospective analysis which found the following that is relevant for this study:

- There is a tension between open inquiry and the need to guide scientific investigations.
- There is a tension between student invested theories and accepted theories.
- There is a tension between the scientific research culture and the school culture. (ibid., pp.593 – 594)

Petrus (2015: 453) compared the performance in direct current electricity of 100 first-year science education students enrolled at a South African university. Some had been exposed to the new science curriculum at school level while the rest had studied the old curriculum. Although no statistically significant differences were found between the pre- and post-tests for the two groups, a significant recommendation is that teaching strategies should be learner-centred since the intervention caused substantial gains in scores for both groups.

In the next section I outline domain-specific pedagogical strategies that are designed within a social constructivist learning environment to help pre-service science teachers develop their conceptual understanding of direct current electricity.

2.9 A rationale for the choice of teaching strategies

> Becoming a professional science teacher is not a case of learning a predefined set of procedures and a static body of knowledge; it is about engaging with a dynamic and exciting subject and facing the challenges of presenting it to students in an accessible way.
> (Bishop & Denley, 2007: 2)

Claxton (1997, cited by Bishop & Denley, 2007:2) contrasted “knowing what to do” with “knowing what to do when you don’t know what to do”. ‘Knowing what to do’ is like technical rationality – a knowledge base within the profession which can be drawn upon to guide practice. ‘Knowing what to do when you don’t know what to do’ is about *having a repertoire of tools to construct solutions to as yet undefined problems* – a different sort of intelligence for these changing times. The science teacher is confronted with different scenarios within different contexts across classrooms and has to draw on tacit knowledge in response to unimagined situations. This also implies that the teacher must develop the repertoire of tools to respond and face up to the challenge in the science classroom.

An examination of the literature in science education reveals a variety of teaching strategies which are fundamental to developing pre-service science teachers’ conceptual understanding. Coll and France (2005) as well as Spier-Dance, Mayer-Smith, Dance and Khan (2005) have shown that the use of models and analogies within the pedagogy of science education are important for developing and promoting conceptual understanding in science. Sadler (2006: 323) posited the view that argumentation is a means for promoting conceptual development in science while Cross, Taasoobshirazi, Hendricks and Hickey (2008: 839) contended that students exposed to argumentation can address misconceptions and develop a better understanding of science. McNally (2006: 423) maintained that new teachers can develop a confident pedagogy by teaching science by means of investigations. Teaching science as inquiry also requires that teachers develop students’ understanding of science concepts (Crawford, 2007: 614).

2.9.1 Models and modelling in science education

The National Science Foundation (2013: 1) defines modelling as the process whereby scientists represent ideas about the world and make changes to these as new evidence and understandings arise. A scientific model is a representation of a system such as an electrical circuit or solar system – the representation can be a drawing, equation, graph or physical replica (ibid., p.2). What is important is how the model is used to provide a causal explanation for a phenomenon. In chemistry, for example, one would use the model of the atom to explain observations occurring at the macroscopic level. When electric current flows in a conducting wire one might see the light shine, but the moving charges cannot be seen. A model is needed to explain this phenomenon. Harrison and Treagust (2000: 1012) argued that models must enhance investigation, understanding and communication.

Mulhall, McKittrick and Gunstone (2001: 576) argued that the concepts of electricity are particularly problematic. The concepts are highly abstract and complex which make their understanding dependent on models, analogies and metaphors. Phenomena cannot be observed directly, but only the consequences thereof are observable - lighting of a bulb, reading on a meter, etc. (ibid., p.579). The authors raised the question: What do we expect students to learn when we talk of “conceptual understanding” in electricity, and how might this change with the level of education? They concluded that it is crucial to use models/analogies in the teaching of electricity.

Schwarz, et al. (2009: 633-635) advanced the idea of a model as a representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena. They include four elements:

- Students construct models consistent with prior evidence and theories to illustrate, explain, or predict phenomena.
- Students use models to illustrate, explain, and predict phenomena.
- Students compare and evaluate the ability of different models to accurately represent and account for patterns in phenomena, and to predict new phenomena.
- Students revise models to increase their explanatory and predictive power, taking into account additional evidence or aspects of a phenomenon.

The authors argued that the pedagogical benefits that can be derived lies with the student being able to use the model to articulate his/her understanding of a phenomenon. They outline a useful learning progression for understanding models as generative tools for predicting and explaining – from students using a model to simply illustrate a phenomenon to constructing a model in a range of domains to help their own thinking (ibid., p.640).

Gilbert (2004: 117-118) outlined various types of models:

- A *mental model* is a personal representation formed by an individual.
- An *expressed model* is when a version of the mental model is placed in the public domain.

- A *consensus model* obtains when a social group agrees on a common expressed model.
- A *scientific model* obtains when scientists work with a consensus model.
- A superseded scientific model is called a *historical model*.

These models are placed in the public domain by different modes of representation such as the concrete mode, verbal mode, symbolic mode, visual mode and gestural mode. The importance of multimodality in science education is addressed in section 2.9.2.

Akerson, White, Colak and Pongsanon (2011: 222) maintained that modelling is a higher-order skill that includes process skills used in scientific inquiry. It is therefore important that teachers know the value of scientific models, and exposure to the use thereof is necessary for them to implement it in their classrooms. Coll and Lajium (2011: 14) argued that research is needed to understand the prevalence of pre- and in-service teachers' understanding of models and modelling. Sengupta and Wilensky (2011: 142) highlighted the fact that with concepts such as electric current, representations are mostly symbolic and mathematical. Students are unable to relate behaviour of charges at a microscopic level to that which they observe at a macroscopic level. The implication is that they need more explicit teaching that focuses on this.

2.9.2 Multimodality in science education

Developing the students' conceptual understanding in science entails a plethora of representations that allow the student to engage with disciplinary knowledge. The role that language and text plays in the process of communicating this knowledge by the teacher cannot be discounted. In adopting various pedagogical strategies within different contexts, the science teacher uses a multiplicity of modes which Airey and Linder (2009: 40) term a *'critical constellation of modes'* in physics. The authors propose that multimodal teaching has the potential to lead to better and more comprehensive outcomes, and research should be carried out 'into which constellation of modes best opens up the possibility for experiencing each of the particular ways of knowing of physics' (ibid., p.42). Van Heuvelen (1991: 891) argued that student solutions are devoid of any qualitative understanding whereas physicists rely on qualitative analysis and representation.

In this section the concept of multimodal representations in science education is explored as fundamental to developing the students' conceptual understanding in science. It is also underpinned by a social constructivist approach as it affords the student multiple opportunities to construct knowledge in the science classroom. In physics this was proposed as a pedagogical technique when Van Heuvelen (1991: 896) stated that "multiple exposures to skills and concepts over extended time intervals can assist in making these permanent".

Prain and Waldrip (2006: 1843-1844) highlighted the fact that learning concepts and methods in science entails understanding and conceptually linking different representational forms. This focus on multimodal representations is also consistent with the nature of scientific discourse. According to these authors the following definitions are useful:

- **Mode** refers to the type of representation entailed in the resource (visual, experiential, 3D written, graphic, numerical).

- **Multiple** representations refer to the practice of re-representing the same concept through different forms, including verbal, graphic, and numerical modes, as well as repeated student exposures to the same concept.

- **Multi-modal** refers to the integration in science discourse of different modes to represent scientific reasoning and findings.

An important aspect is the ability of the student to interact between the different modes and to be able to translate from one mode to the other. The challenge is to develop a teaching and learning environment that allows for this type of interaction, and which caters for the different learning styles and abilities of the students. The different representational forms include such categories as descriptive (verbal, graphic, tabular), experimental, mathematical, figurative (pictorial, analogous and metaphoric), and kinaesthetic or embodied gestural understandings or representations of the same concept or process (p.1844). In basic current electricity, for example, the students can engage with scientific investigations, computer simulations, 3D models, diagrams, graphs, verbal accounts, etc.

In their exploratory study, Prain and Waldrip (2006: 1843) aimed at identifying initial beliefs and practices of a group of teachers and students (Years 4–6) in Australia when the students engaged with multiple representations of the same science concepts. A multi-site case-study approach was employed with qualitative and quantitative methods; they found that while teachers used various modes to engage students and assess learning, they were not systematic in their focus on student integration and translation across modes. The study also established that various factors affected students' understanding of different modes, and that students who recognised relationships between modes demonstrated better conceptual understanding than students who lacked this knowledge. Tytler and Prain (2010: 2075) cite Reif and Larkin (1991) who argued that understanding a concept in science involves being able to operate flexibly and coherently with a range of associated representations, and this process will involve both deductive and inductive logical modes, and non-formal personal and perceptual associations.

Tang, Chee and Yeo (2011: 1776) cite Yore and Treagust (2006) who posit the view there is a general lack of a multi-representational framework that investigates *how* various representations and representational transformations (from one mode to another) promote conceptual understanding. There is also a need to conduct empirical research to show how multiple modes of representations can be used to support science achievement. Congruent with the outline above, Tang *et al*. define an *instructional representation* as a particular form of expression such as a written text, analogy, equation, table, graph, diagram, and simulation. A *mode* of representation, or *modality*, is a semiotic (meaning-making) resource system moulded and repeatedly used overtime in a community. An important point of departure is that no two different representations are equivalent, and translations between representations are not as unproblematic as many would assume. The question which they pose is how are appropriate meanings constructed through the use of any kind of representation (or combination of representations) rather than which is the right representation to use. The results of the study of the role of multimodalities in representing the work-energy concept with grade 9 physics students showed that the thematic integration of multimodalities is both difficult and necessary for students in order to construct a scientific understanding that is congruent with the physics curriculum.

A further consideration of multimodal representations locates it within the broader framework of scientific literacy. As Yore and Hand (2010: 94) elaborate:

Positioning multiple representations, multiple modality, and textual, semiotic and symbolic modes within the larger framework of science literacy for all, can be seen by realizing that these modes and their use in science play roles in both the understanding of science and the fundamental literacy in science that allow scientists and students to construct understandings and to report and argue these ideas with others.

Whether it is fundamental literacy or the level at which scientists engage with research and interrogate ideas in order to establish scientific knowledge, the role of multimodalities is important. Yore and Hand (2010: 96) argued further that the embeddedness of representations, experience, argument, and printed words appears to be an indicator of successful integration of mental images, conceptual understanding, and stored meaningful knowledge.

The focus on multiple representations of science concepts is consistent with a social constructivist approach to learning science which is less restrictive than a traditional textbook approach. A review of the research has the following implications for teaching:

1. It is important for teachers to utilise multiple and multimodal representations to enhance student learning.

2. It is important for teachers to assist students in scaffolding their understandings using multiple and multimodal representations.

3. Multiple and multimodal representations need to be carefully planned into the teaching and learning material.

Recent physics education research has also highlighted the importance of multiple representations within the discipline:

- Unpacking representations is a vital aspect of coming to appreciate the disciplinary affordances of representations of attaining a more comprehensive access to the disciplinary knowledge. (Fredlund, Linder, Airey & Linder, 2014: 9)

- In a case study which focused on how a particular set of representations facilitated meaning making in small-group discussions, it was found that representation affordance is critically related to how the representations get situated in a learning environment. (Enghag, Forsman, Linder, MacKinnon, & Moons, 2013: 643)

- For the teaching and learning of science a productive way of thinking about the signification of the representations used is in terms of their affordance which is the inherent potential of that representation to provide access to disciplinary knowledge. It is the collective disciplinary affordance that underpins appropriate holistic meaning-making. (Linder, 2013: 44)

- When the interpretation and understanding of discipline-specific representations such as models, graphs, tables and diagrams is integrated

> with the verbal and written language it leads to meaning-making and knowledge building. (Nichols, Hanan & Ranasinghe, 2013: 180)

2.9.3 Problem-solving in physics education

Students who enter introductory physics courses use formula-centred problem-solving strategies and their status remains the same when they leave the course (Van Heuvelen, 1991: 891). They merely attempt to find the value of an unknown quantity without using any qualitative tools that help them to develop understanding. This approach can be contrasted with that of experts who often apply qualitative representations such as diagrams to help themselves understand problems before they use equations to solve them quantitatively (Van Heuvelen & Zou, 2001: 184). It is through engagement with multiple representations that understanding emerges in physics. Students who are exposed to such an environment are likely to construct multiple representations to solve problems themselves (De Cock, 2012:1). Rosengrant, Van Heuvelen and Etkina (2006: 52) also suggested that “if the instructor consistently models certain problem solving strategies in class and students have ample opportunities to practice these strategies; the students will use them to solve a relatively difficult problem”.

While improving conceptual understanding might be a desired outcome, it cannot be assumed that this follows from enhanced problem-solving ability (Fraser, Timan, Miller, Dowd, Tucker, & Mazur, 2014: 6-7). The latter should not be neglected as the student needs it for reasoning with numbers and graphs. It has also been shown that research-based instructional strategies are more effective in improving students’ conceptual understanding and problem-solving skills (ibid., p.7).

At the University of Massachusetts a greater emphasis was placed on concepts and qualitative reasoning to overcome the shallow understanding of concepts, and the narrow set of problem solving skills that students developed (Dufresne, Gerace, & Leonard, 1997). Special representations were used to teach physics in one of three ways:

- To elucidate a problem (e.g. draw a sketch).
- As the subject of a problem (e.g. student must draw a graph).
- As a step in a formal procedure (e.g. draw free-body diagram).

(ibid., p.271)

2.9.4 The role of argumentation in science education

Research in science education has been dominated by a constructivist perspective in the past few decades that had its roots in Piagetian cognitive structures (Cross, Taasoobshirazi, Hendricks and Hickey, 2008: 837). These research studies explored children's prior knowledge, and alternative conceptions and theories of conceptual change were developed (Simon and Richardson, 2009: 470). But the proliferation of curriculum materials and pedagogical approaches had a limited impact, because teachers still lacked the pedagogical content knowledge to be effective science teachers. A research focus on the nature of science also emerged along with studies of students' epistemological beliefs and the role of argumentation in science education. Argumentation has become a central practice in science education and if students understand the norms of scientific argumentation, it can lead to a better understanding of the epistemological bases of scientific practice as well as developing a better conceptual understanding of science (ibid., p.470).

Barak and Dori (2009: 461–462) have argued that adopting a constructivist-oriented pedagogy that builds on the theory of social constructivism in the Vygotskian tradition can enhance critical thinking and argumentation skills. Scientific knowledge is constructed through social interaction with others in a co-operative learning environment. The educational discourse is characterised by discussion, debate, disagreement and the provision of evidence to persuade your peers of your viewpoint. The role of the educator in this scenario is to ensure that the correct scientific understanding is ultimately mediated. The students' skills are concomitantly enhanced since 'argumentation is a crucial communicative activity in our modern world, which involves the use of reasoning, evidence, and claims to put forward a case' (ibid., p.471).

The adoption of an inquiry-based science classroom has meant that the transmission mode of teaching has shifted 'toward teaching strategies that require students to develop skills of argument such as making claims, using evidence, and requiring peers to evaluate claims based on the strength of evidence' (Martin & Hand, 2009: 18). This focus on scientific inquiry, however, has not been without problems as teachers come from a tradition of 'discovery learning' and a 'hands-on science' approach (ibid., p.18). Studies have shown that students gain in conceptual understanding when they work collaboratively; engage in discussion to solve problems, and use critical thinking skills to build their scientific knowledge base. The classroom environment thus becomes characterised by student-student talk and not teacher-student talk.

Sampson and Clark (2008: 448) reviewed the literature on argumentation in science education and indicate that substantial variation exists in the analytic frameworks that have been developed to study the scientific arguments that students construct. They state that current research indicates that learning how to engage in productive scientific argumentation to propose and justify an explanation through argument is difficult for students (ibid., p.449). The term "argument" in the review refers to the artifacts that a student or a group of students create when asked to articulate and justify claims or explanations whereas the term "argumentation" refers to the process of constructing these artifacts (ibid., p.447).

Toulmin's argument framework suggests that the statements that make up an argument have different functions that can be classified into one of six categories: claims, data, warrants, backings, qualifiers, and rebuttals (Sampson and Clark, 2008: 450). These are illustrated in figure 2.4 below.

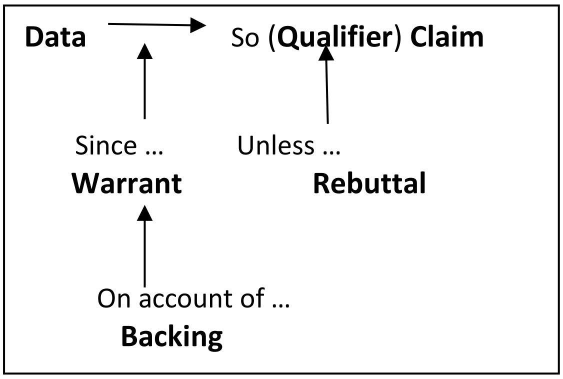


Figure 2.4   Toulmin's argument pattern

Claims are assertions and data are the foundations for those claims. Warrants are comments that are used to justify why data are relevant to the claim. The warrant's strength is indicated by the inclusion of a modal qualifier. The backings of an argument are the comments that are used to establish the general conditions that strengthen the acceptability of the warrants so that the connection between the data and the claims will not be questioned. Finally, a rebuttal indicates the “circumstances in which the general authority of the warrant would have to be set aside” (Sampson and Clark, 2008: 450 – 451).

Argumentation is critical to producing, evaluating, and advancing scientific knowledge and should be a core component of school science—as a way to help students engage with the social construction of scientific ideas as well as learn about the workings of the scientific enterprise (Bricker and Bell, 2008: 474). The implication is therefore that PSSTs should also be exposed to argumentation since they will ultimately be teaching science in the school classroom. van Eemeren and Grootendorst (2004) define argumentation as “. . . a verbal, social, and rational activity aimed at convincing a reasonable critic of the acceptability of a standpoint by putting forward a constellation of propositions justifying or refuting the proposition expressed in the standpoint” (cited by Bricker and Bell, 2008: 477).

Simon, Erduran and Osborne (2006: 235) investigated the teaching of argumentation in secondary science classrooms. To assess the quality of arguments of 12 teachers from schools in the greater London area, analytical tools were derived from Toulmin’s argument pattern. The authors conclude that it is possible for science teachers to adapt and develop their practice in such a way as to bring about a change in the nature of classroom discourse. They suggest that to help teachers progress in their teaching of argumentation, the focus of professional development should be on teachers’ existing understanding of the importance of evidence and argument in science and on their implicit goals of teaching and learning science (ibid., p.256).

von Aufschnaiter, Erduran, Osborne and Simon (2008: 101) investigated junior high school students' processes of argumentation and cognitive development in science and socio-scientific lessons. The quality and frequency of students' argumentation was analyzed using a schema based on the work of Toulmin. Students' development and use of scientific knowledge was also investigated, drawing on a schema for determining the content and level of abstraction of students' meaning-making. The findings show that (a) when engaging in argumentation students draw on their prior experiences and knowledge; (b) such activity enables students to consolidate their existing knowledge and elaborate their science understanding at relatively high levels of abstraction.

It has been reported that there is limited research on how teachers, in-service or pre-service, construct and learn to teach arguments on scientific issues (Ozdem, Ertepinar, Cakiroglu, Erduran, 2013: 2560). In the domain of current electricity Kelly, Druker and Chen (1998: 849) studied how, and under what conditions, students justified their claims while attempting to solve a performance assessment task. They found great variability in students' argumentation patterns and suggested that further research be done to analyse student argumentation discourse in small groups and whole-class discussions. In particular, the sufficiency of the evidence provided from a scientific perspective needs to be analysed when students use their subject-matter knowledge when they are engaged in problem-solving (ibid., p.867).

Osborne wrote a thought provoking article 'Science Education for the twenty-first century' (2007: 173–184). He said that in order to become a critical consumer of science, what is required is knowledge and understanding of three things in science education:

a. The scientific content;

b. The scientific approach to enquiry;

c. Science as a social enterprise – that is the social practice of the community.

He proposed dialogic interaction for the students to construct meaning as they present their arguments with the necessary evidence. When this dialogue is carefully scaffolded by the teacher, it can allow the students to work in the zone of proximal development as they internalise their understanding (ibid., p.180). Figure 2.5 shows five dimensions that influence teachers' pedagogy in science. Those who are able to open up the space for students to develop their understanding through dialogical discourse lie to the right of the spectrum (ibid., p.182).

Teacher is anxious about their understanding	*1. Teachers Knowledge and Understanding of the Nature of Science* ←→	Confident that they have a sufficient understanding of NOS
Dispenser of knowledge	*2. Teacher's Conceptions of Their Own Role* ←→	Facilitator of learning
Closed and authoritative	*3. Teachers' Use of Discourse* ←→	Open and dialogic
Limited to knowledge gains	*4. Teachers' Conception of Learning goals* ←→	Includes the development of reasoning skills
Student activities are contrived & inauthentic	*5. The Nature of Classroom Activities* ←→	Activities are owned by students and authentic.

Figure 2.5 The five dimensions of practice that influence teachers' pedagogy when teaching about science. (Osborne 2007: 181)

In the discipline of science education the term socio-scientific issues has emerged 'to represent controversial social issues with conceptual, procedural, or technological ties to science' (Sadler and Donnelly 2006: 1463–1465). These issues typically stem from biotechnology and environmental problems; examples include genetic engineering, cloning, local pollution issues and global climate change. They are usually contentious and require evidence to back any claims that are made; they therefore lend themselves to argumentation as a pedagogy that promotes discussion and dialogue. The authors investigated how science students' content knowledge and moral reasoning contribute to argumentation in the context of genetic engineering issues (ibid., p.1464). They found no qualitative evidence of participants actively using accurate science conceptions while resolving genetic engineering problems, but this does not rule out a relationship between content knowledge and argumentation quality. In the context of Natural Sciences these results are relevant with regard to the generation of electricity which includes the burning of fossil fuels and nuclear energy. The emission of carbon dioxide and sulphur dioxide gas into the atmosphere lead to the formation of acid rain.

Acar, Turkmen and Roychoudhury (2010: 1191–1206) reviewed the literature and highlighted the fact that students have problems evaluating the evidence, nature of science conceptualisations and value-based decision-making in socio-scientific argumentation. This is because of the uncertainty of the evidence in socio-scientific issues, students' inability to grasp the nature of science, and their use of emotive and intuitive reasoning. It was also noted that explicit instruction on argumentation addressing socio-scientific issues has no consistent effect on quality of argumentation. It is recommended that 'a value-focused decision-making framework, in which students can consider their values and examine different alternatives in the light of evidence, can be a remedy to aforementioned problems in socio-scientific argumentation' (ibid., p.1204).

Kuhn and Reiser (2006: 8 - 10) have argued that students must be helped to use evidence when constructing and evaluating knowledge claims by placing them in contexts that value evidence. In this regard, Berland and McNeill (2010: 766) described the learning progression they developed to understand student argumentation and the environment that supports the practice thereof. They differentiate between the argumentative process and product. The former is a reasoned piece of discourse in which a claim has been justified whereas the latter focuses on the social interaction between participants (ibid., p.772). When looking at the evidence that supports a scientific claim, it is important to examine the appropriateness and sufficiency of the evidence by considering its relevance and complexity respectively (ibid., p.774).

Choi, Klein and Hershberger (2014: 6) have argued that "creating evidence-based explanations, connecting explanations to accepted scientific concepts, or justifying and communicating investigations are rare". In this DBR study, when students present their model that represents an illustration of the principles of basic current electricity, it is expected that they explain and support/justify the claims that they make with the relevant evidence.

2.9.5 Scientific investigations

Scientific investigation is the way in which scientists and researchers use a systematic approach to answer questions about the world around us (van

Tonningen, 2014: 1). It includes the processes of “observing, questioning, planning, predicting, testing, collecting, recording and analysing data, and drawing conclusions” as shown in figure 2.6 below.

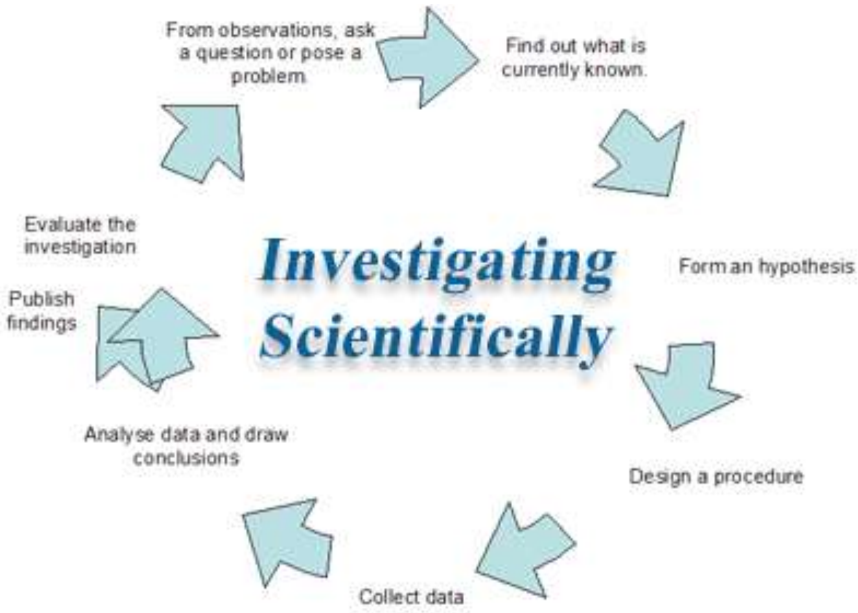


Figure 2.6 Scientific investigation process, accessed at

http://www.curriculumsupport.education.nsw.gov.au/primary/scitech/investigate/image/cycle.gif

Millar (2004: 2) uses the term ‘practical work’ to refer to “any teaching and learning activity which at some point involves the students in observing or manipulating the objects and materials they are studying”. For the purposes of this discussion this term can also be appropriated as its usefulness lies in the fact that it is not confined to a laboratory setting. Science investigations are a part of practical work and are also not confined to the laboratory. Practical work promotes the engagement and interest of students as well as developing a range of skills, science knowledge and conceptual understanding (SCORE, 2009: 1).

Bell (2005: 6) has argued that in the "educational framing of inquiry-based science education, laboratory-related activities are interwoven into inquiry sequences". The focus is on framing research questions, designing and executing experiments, gathering and analysing data, and constructing arguments and conclusions. From a social constructivist perspective students develop a deeper understanding of concepts when they construct meaning from these activities as opposed to being exposed to a knowledge transmission approach. This relates directly to the motivation to move students from a traditional didactic approach to an inquiry-based approach in science education.

Mäntylä and Hämäläinen (2015: 699) analysed the laboratory reports of pre-service physics teachers which established the empirical formulae of quantities of electric current, voltage and resistance. The study found that the teachers understand the basic idea of how quantifying experiments establish the quantities and laws, but are not able to argue it in a justified manner. In an investigation of the use of an open guided inquiry laboratory with a group of pre-service physics teachers it was found that the environment provides support for pre-service teachers to discover the limits of their understanding of subject matter knowledge (Nivalainen, Asikainen & Hirvonen, 2013: 449). It also allows them to construct knowledge in a different kind of environment from any they had possessed previously, and helps them to understand the possibilities of practical work in teaching.

In this study a *guided inquiry* approach was adopted in which the materials and the problem are given, and students can examine the given problem by means of several procedures. In contrast, the *open inquiry* approach provides the students with only the materials, and they then devise the problem by themselves and select the procedures for investigation (ibid., p.453).

2.9.6 Summary

This chapter outlined the literature in developing a conceptual framework for this study which falls within the domain of science teacher education. The changing education policy landscape was summarized, and in particular the revision of the policy relating to pre-service teacher education is relevant to this study. This was followed by an examination of the philosophy of pragmatism which underpins DBR, and scientific inquiry was motivated as the primary means to develop PSSTs understanding in science. The development of PSSTs process skills was also coupled with scientific inquiry. Social constructivism was defined as the theory that underpins scientific inquiry and it is the approach used during the teaching experiment.

The importance of PCK was highlighted and the literature relating to the teaching and learning of basic current electricity was comprehensively reviewed. The concept of conceptual understanding has been clarified in terms of it being a construct measured when students demonstrate certain skills such as interpreting a graph, finding qualitative or quantitative solutions, etc. The roles of models, multimodality, argumentation and scientific investigations in developing and promoting PSSTs conceptual understanding in science have been examined.

The emergence of DBR has been strong in mathematics education, particularly in the Netherlands. A lot of studies have also focused on virtual learning environments in different domains. This study would contribute to the development of a learning environment in physics education by focusing on direct current electricity. In particular, it uses the existing literature to infuse elements of pedagogical approaches into the teaching and learning environment that would develop the conceptual understanding of PSSTs. The study would highlight the characteristics of the learning environment by detailing the sequence of events as they were documented in the study. By outlining a conceptual trajectory in the domain of direct current electricity for PSSTs, its main aim is to establish whether their conceptual understanding was developed as a consequence of the intervention. However, DBR is unique because it does not look for causal relationships by isolating variables, but rather seeks to understand how learning occurs.

The next chapter looks at the research design in more detail by defining DBR and outlining its characteristics. The content and pedagogical dimensions of the teaching experiment are expanded upon, and the phases of the design are demarcated.

CHAPTER 3

RESEARCH DESIGN

This chapter outlines the rationale for design-based research (DBR) and explains why the transformative conjecture-driven teaching experiment is adopted in particular. It expands on the content and pedagogical dimensions of the transformative conjecture-driven teaching experiment and provides details about the phases of the design research process. It concludes with an explanation of a retrospective analysis.

3.1 The rationale for design-based research

> The appreciation of quasi-experimental research design is natural: science teachers and science education researchers tend to begin their studies in physics, chemistry, or biology, where an (quasi-)experimental setting is conventional. Thus, science teachers may perceive results gained from research using methods other than quasi-experimentation – e.g. interviews – as being nothing more than personal opinion. However, science teaching and learning phenomena is very difficult to treat as an independent or dependent variable. (Juuti & Lavonen, 2006: 55)

As science teachers we are steeped in the tradition of the scientific method and tend to adopt research methodologies that use experimental design and the concomitant rejection or acceptance of hypotheses. The philosophical framework underpinning this approach, scientific realism, is found in the positivist arguments used to describe knowledge generation in the physical sciences (Lodico, Spaulding & Voegtle, 2010: 13). When the researcher has been exposed to quantitative research methodology, as in this case, then the journey to explore other methodologies can be fraught with difficulty. Extensive reading of the literature broadens your perspective especially when methodologists want to rigidly adhere to quasi-experimental design whilst debunking all other methodologies. Juuti and Lavonen quoted above capture the essence of the argument that controlling variables is problematic when conducting research on teaching and learning in science education. The context and socio-cultural influences impact on the research environment and may very well contaminate the findings.

The latter point is reinforced by Berliner (2002:18) when he argued that broad theories and ecological generalisations fail in education because they cannot incorporate the enormous number or determine the power of the contexts within which human beings find themselves. Humans in schools, in particular, are embedded in complex and changing networks of social interaction and the participants in those networks have variable power to affect each other from day to day. The ordinary events of life (a sick child, divorce, migraine headaches, etc.) all affect doing science in school settings by limiting the generalisability of educational research findings. One possible reason for doing design research is to account for the messiness of the classroom and to produce an artefact / strategy that may be used in such a setting (Prediger, et al., 2015: 880).

This research study of the development of pre-service science teachers' conceptual understanding of direct current electricity falls within the emerging paradigm of a design study because it involves "the study of learning in context through the systematic study of instructional strategies and tools" (Design-Based Research Collective, 2003: 5). The term design study has evolved from various terms given to the same research approach such as "design research", "design experiment", "teaching experiment" and "design-based research methods" (Confrey, 2006: 135).

The choice of chapter heading 'research design' as opposed to 'research method' is also deliberate. Research method has connotations of following rigid computational procedures for analysing data and has tended to be associated with statistics-oriented courses (Lesh, Lovitts and Kelly, 2000: 19). Research design is more about constructing a complex design when dealing with human constructs such as classrooms, schools, programmes and conceptual systems. The models that are used to describe, explain and predict the behaviours of these systems are also the products of human construction (ibid., p.22). Science and mathematics education research deal with these complex, interacting systems and should provide information that informs practice in a more meaningful way. The aim of using design-based research is thus to bridge the gap between research and praxis.

Educational design-based research is a relatively new research approach and the fact that small groups across several disciplines are responsible for its development means that it is not widely discussed in textbooks on research methodology (Plomp, 2013; Bakker & van Eerde, 2015). DBR "aims both at developing theories about domain-specific learning and the means that are designed to support that learning" (Bakker & van Eerde, 2015: 430). In the process of the research useful educational materials are produced and the theory that underpins its implementation is also provided. While the overall aim of DBR is as stated above, there might be a descriptive or comparative aim which is espoused during different stages of the research.

3.2 Definition of a design study

Plomp (2013: 15) proposes two definitions of a design study depending on the purpose of the study:

(a) *The systematic analysis, design and evaluation of educational interventions with the dual aim of generating research-based solutions for complex problems in educational practice, and advancing our knowledge about the characteristics of these interventions and the processes of designing and developing them.*

(b) *The study of educational interventions (such as learning processes, learning environments and the like) with the purpose to develop or validate theories about such processes and how these can be designed.*

The former seeks to develop research-based solutions for complex problems in educational practice while the latter is the development or validation of a theory through the design of a learning environment or learning trajectory. The DBR approach adopted in this study would fall within the latter as it seeks to validate processes of teaching and learning through the intervention of a transformative conjecture-driven teaching experiment. That said, however, the approach is driven by extensive research about the content as well as the pedagogy. As Plomp (2013: 26) argued, many researchers employ both the development and validation study orientation in their research.

3.2.1 The main characteristics of design-based research

- Design-based research is pragmatic because its goals are solving current real-world problems by designing and enacting interventions as well as extending theories and refining design principles.

- Design-based research is grounded in both theory and the real-world context. It is conducted in collaboration with practitioners, and is much more likely to lead to effective application.
- In terms of research process, design-based research is interactive, iterative and flexible.
- Design-based research is integrative because researchers need to integrate a variety of research methods and approaches from both qualitative and quantitative research paradigms, depending on the needs of the research. Data from multiple sources serve to confirm and enhance the credibility of findings.
- Design research is contextualized because research results are connected with both the design process through which results are generated and the setting where the research is conducted. (Wang and Hanafin, 2005: 8)

Prediger, et al. (2015: 879) explained the common characteristics of design research as follows:

- The intent of design research is to create and study new forms of instruction.
- The goal of design research is to generate theories about the process of learning and the means of supporting that learning.
- Theory prospectively informs the design for the design experiment, and is further developed in the retrospective reflection on deviances between the expected and the observed teaching and learning processes.

- Typical for design research studies are the iterative cycles of invention and revision; when conjectures are refined during an experiment or between experiments.
- The emphasis on ecological validity and practice-orientation reflects its pragmatic roots.

Shavelson, Phillips, Towne and Feuer (2003:25) argued that “the strengths of design studies lie in testing theories in the crucible of practice; in working collegially with practitioners, co-constructing knowledge; in confronting everyday classroom, school, and community problems that influence teaching and learning and adapting instruction to these conditions”. However, design-based research has also been criticised on numerous fronts for its supposed methodological feebleness. It is time consuming, under-conceptualised, over-methodologised, and it is difficult to make generalisations across participants (Dede, 2004; diSessa & Cobb, 2004). Ford and Forman (2006: 141) offer a rebuttal by arguing that to criticise design experiments from a pure science perspective, as is most often the case, is erroneous because the underlying rationales are different. Research quality cannot be judged by alignment with templates and tools without due consideration of the aims. The authors propose three methodological principles for research on teaching and learning:

- Rigour: identifying learning outcomes that stem from the instructional intervention by looking at assessed performance.
- Value: being able to infer the educational value of the instructional intervention.
- Generality: educational research should provide general power to improve learning. (ibid., p.142)

The theoretical rationale for selecting design studies as a methodology is also supported by the scholarship of Piaget, Vygotsky and Dewey which produced theories about instructional guidance, and that support views of the classroom as complex and conditional rather than deterministic. Practice can be guided by means of explanatory frameworks accompanied by data, evidence, and argument. The theory of design studies incorporates this epistemological view of classroom praxis (Confrey, 2006:138). The data and evidence are obtained by studying student work, video records, and classroom assessments.

Design-based research can be conducted in a wide range of settings:

- One-on-one (teacher-experimenter and student) design experiments in which a research team conducts a series of teaching sessions with a small number of students.
- Classroom experiments in which a research team collaborates with a teacher (who might be a research team member) to assume responsibility for instruction.
- Pre-service teacher development experiments in which a research team helps organize and study the education of prospective teachers.
- In-service teacher development studies in which researchers collaborate with teachers to support the development of a professional community.
- School and school district restructuring experiments in which a research team collaborates with teachers, school administrators, and other stakeholders to support organizational change.

(Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003: 10-11)

This study focuses on pre-service science teachers in the second year of their studies to complete a Bachelor of Education degree in the intermediate phase (Grades 4 – 6) or senior phase (Grades 7 – 9). These students are studying Natural Sciences as a school subject as part of their curriculum specialization.

3.3 Design-based research and pragmatism

Pragmatism focuses on action to acquire new knowledge to attain the objective of improving practice. Dewey's pragmatic philosophy also resonates with design-based research because of its practical orientation where the consequence and possibilities of an idea holds value – ideas are educative only to the extent that they inspire action (Wong, Pugh & the Deweyan Ideas Group, 2001: 323). The cognitive mode of experience supports actions and knowledge helps a teacher to teach more intelligibly – the role of science education research is precisely to help reach this goal in the science learning environment (Juuti & Lavonen, 2006: 58).

Design-based research is reinforced by the philosophical framework of pragmatism. Lodico, *et al.* (2010: 17) summarized pragmatism as follows:

- The immediate reality of solving educational problems should be the focus of educational research.
- Educational settings and problems can be studied using any method that accurately describes or solves a problem.
- Research should strive to find ways to make education better.
- Researchers should collaborate with participants to fully understand what works.
- Theories and hypotheses are useful tools in helping to improve education.

Those who engage mixed methods research mostly adopt the pragmatic worldview (Tashakkori & Teddlie, 2003; Creswell, 2009; Mertens, 2009). In this DBR study qualitative as well as quantitative data are analysed from student assessments as well as transcriptions of video data.

3.4 Addressing the research problem

This study seeks to answer the question: What inquiry-based science teaching strategies will foster the development of pre-service science teachers' conceptual understanding of direct current electricity?

Sub-questions:

a) How do scientific investigations promote multimodal skills and contribute to the development of pre-service science teachers' conceptual understanding of direct current electricity?

b) How does problem-solving contribute to the development of pre-service science teachers' conceptual understanding of direct current electricity?

c) What argumentation patterns do pre-service science teachers produce to demonstrate their conceptual understanding of direct current electricity?

It should be noted that the formulation of the main research question in DBR is not arbitrary as it expresses the search for characteristics regardless of whether the aim is to develop theory or seek validation (Plomp, 2013: 27).

The following section will look at "*the transformative teaching experiment*" as a research approach utilised in this study to answer these research questions.

3.5 The transformative teaching experiment as research design

Confrey and Lachance (2000: 232-233) coined the term *transformative and conjecture-driven teaching experiment* in their desire to reform teaching practice by creating and investigating new instructional strategies. It is also motivated by their commitment to equity, attempting to create equal opportunities for all students to participate in and succeed at mathematics. This ideological stance informs their research design which comprises conjectures rather than hypotheses.

A conjecture is an inference based on inconclusive or incomplete evidence and in the context of education it may pertain to how a subject is conceptualised or taught. It is a means to reconceptualise the content and pedagogy and stems most often from dissatisfaction with current practice (ibid., p.235). A conjecture is not an assertion waiting to be proved or disproved like a formal hypothesis in an experimental design approach because it can be revised while the research is in progress. There are two dimensions to the conjecture, viz. a content dimension that addresses what should be taught, and a pedagogical dimension that addresses how the content should be taught. These dimensions are shown in Figure 3.1 which demonstrates how the components all work together.

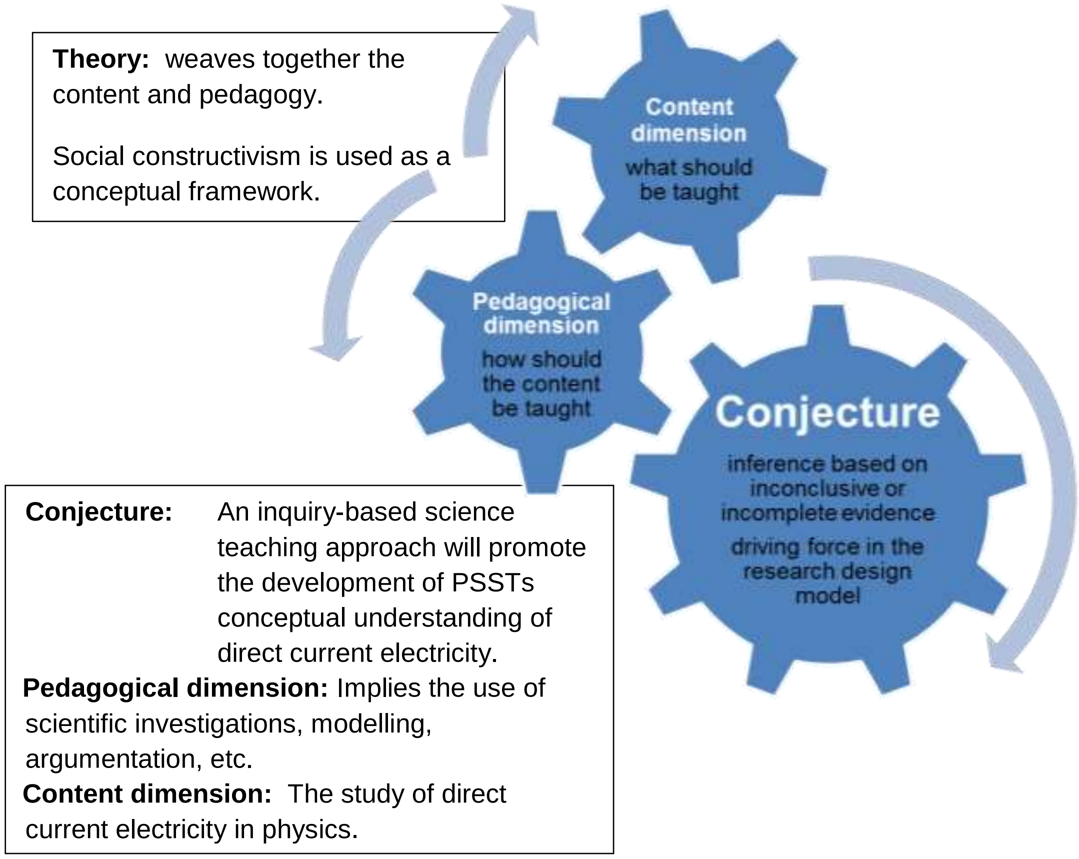


Figure 3.1: The transformative conjecture-driven teaching experiment

Confrey (2006:145) outlined the goal of design research as the articulation of two related concepts: a conceptual corridor and a conceptual trajectory. The conceptual corridor describes the possible space to be navigated successfully to learn conceptual content while students traverse a particular conceptual trajectory during the teaching episode. The idea is to gather data in order to document the nature of all possible fruitful trajectories as students construct their conceptual understanding of the content. There are constraints and obstacles along the way, but formative assessment tasks can guide students through as these serve as landmarks if they are to successfully navigate the conceptual corridor. Figure 3.2 illustrates the conceptual corridor and conceptual trajectory of students during a teaching and learning episode. The teacher must develop teaching strategies that help students construct meaning and understanding of the content. Multiple opportunities should be provided for explanation and argumentation to scaffold their understanding in anticipation of the next learning episode.

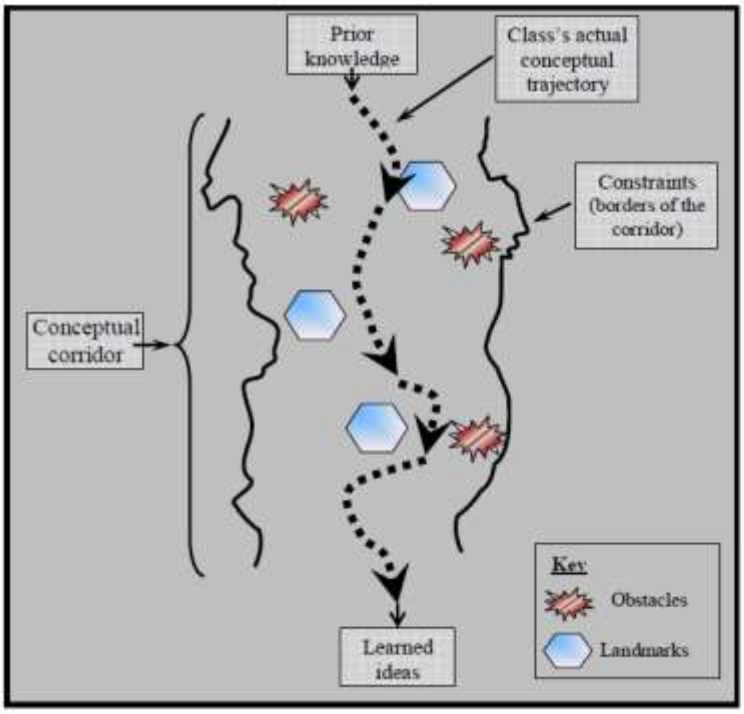


Figure 3.2 The conceptual corridor & trajectory (Confrey, 2006: 146)

3.6 Framing the conjecture

The teaching and learning of current electricity as part of physics straddles the Natural Sciences (GET phase) as well as the Physical Sciences (FET phase) curricula in South Africa. It is also common in Physics at tertiary level for any student following science-related studies. Success at any level requires a good conceptual grasp of the underlying principles of current electricity. Prospective science teachers at primary and secondary school level have a critical role to play in developing learners' conceptual understanding of current electricity. Pre-service science teachers thus need to be exposed to the teaching of electricity (content dimension) to develop their conceptual understanding. Utilising different pedagogical strategies (pedagogical dimension) opens up possibilities of various conceptual trajectories and places them in a position to navigate the conceptual corridor as illustrated above. The desire to see teachers transform their practice in physics from an emphasis on problem-solving using formulae and algorithms to developing conceptual understanding through inquiry-based science underscores the transformative aspect of the teaching experiment.

Confrey and Lachance (2000: 236) argued that the conjecture is necessarily situated in a theory or it cannot be interpreted. The theory appropriate to this study is social constructivism as the development of conceptual understanding of direct current electricity is dependent on the students' prior knowledge. Students' understanding of concepts is interpreted when they demonstrate various skills appropriate to the content and pedagogy. The National Research Council (2000: 61) cited Carlsen (1988) who contended that teachers with deeper conceptual understanding of science allowed their students to engage in discourse more often than teachers with a weaker conceptual background. These teachers also asked students a greater number of high-level questions whereas those with a shallow understanding dominate the classroom discussion.

3.6.1 Motivating the content and pedagogical dimension of the conjecture

- Tsai, Chen, Chou and Lain (2007: 484), in their study of students' conceptual understanding of electric circuits, cite numerous researchers who have found that deep-level conceptual and reasoning problems exist among students. A variety of alternative conceptions were identified independent of age and academic achievement.

- Finkelstein (2005: 1187) stated clearly that "traditionally taught physics classes fail to impart robust conceptual understanding, even for those students who perform well on class examinations". Students are able to do calculations of complex circuits at times, but fail to predict what happens in simpler circuits. The author recommended that the elements that shape the students' understanding in a particular environment needs closer scrutiny.
- Both high school and university students' reasoning regarding direct current resistive electric circuits often differ from the accepted explanations. Students tended to focus on the current in solving problems and to confuse terms, often assigning the properties of current to voltage and/or resistance (Engelhardt & Beichner, 2004: 98).
- Liégeois , Chasseigne, Papin & Mullet (2003: 1129) also contended that students have difficulty in mastering the concept of potential difference because of their everyday experiences of the concept. In their study the students failed to infer the potential difference from the current and resistance, but mostly used the current.
- Mulhall, McKittrick and Gunstone (2001: 575) concluded in their study that electricity is a particular problem, as it involves extremely complex and highly abstract concepts and is thus totally dependent on models/analogies/ metaphors. Research consistently shows very poor student understanding after the teaching of electricity.
- Bricker and Bell (2008: 473) advocated that the science education research community might consider a broader range of argumentation forms and roles

in conjunction with the learning of science. It is critical to advancing scientific knowledge and should be an integral part of school science.

- Success in solving quantitative problems in electricity is not a reliable measure of conceptual understanding as students often cannot answer simple qualitative questions based on the same physical concepts (McDermott and Shaffer, 1992: 995).
- Students become frustrated with the inquiry approach because as learners they want to know the answers. They also feel a disconnection if the assessments do not match the approach (Volkmann, Abell, & Zgagacz, 2005: 847).

3.6.2 The content dimension: Electric circuits

The following section outlines the content dimension of direct current electricity at the primary level that would typically be taught to lay the foundation for the study of more complex electric circuits at the secondary level.

In order for electric current to flow a completed circuit is required as shown in Figure 3.3.

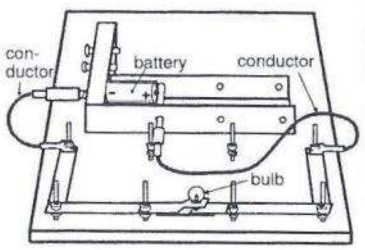


Figure 3.3: A completed electric circuit

This includes:

- A source of energy (battery) that does the work to drive the flow of charges.
- Conducting wires through which these charges must flow.

- A component such as a bulb that converts the electrical energy into light and heat energy.

The components within an electric circuit can be symbolically represented as illustrated in the following table:

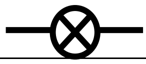
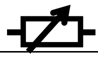
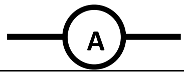
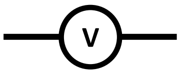
Component	Symbol
Cell and battery	
Switch (open and closed)	
Conductor	
Bulb	
Resistor	
Rheostat	
Ammeter	
Voltmeter	

Table 3.1 Symbols used in basic electric circuit diagrams

3.6.2.1 Conventional current

Conventional current is taken to be the flow of charges from the positive terminal to the negative terminal of a battery as shown in figure 3.4. This is because historically an assumption was made that current is a flow of positive charge before it was known that electrons flow in the opposite direction as in the case of metallic conductors such as copper.

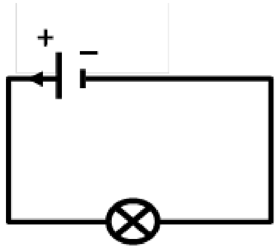


Figure 3.4: Conventional current flow from positive to negative

3.6.2.2 Electric current

Electric current is defined as the amount of charge (Q) that moves past a point in a conductor in one second as shown in figure 3.5.

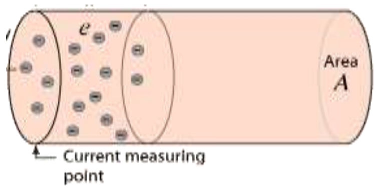


Figure 3.5 Current in a conductor

Thus the magnitude of the current depends on the amount of charge as well as the time that it flows.

We use the symbol I to show current and it is measured in amperes (A). One ampere is one coulomb of charge moving in one second ($C.s^{-1}$).

$$I = Q / \Delta t$$

I = electric current measured in Ampere (A)

Q = charge measured in Coulomb (C)

Δt = time taken in seconds (s)

The amount of charge (Q) can be defined as: $Q = I\Delta t$

One coulomb is the amount of charge that moves past a point in a conductor in 1 second if the current in the conductor is 1 ampere.

3.6.2.3 Ammeter

An ammeter (figure 3.6) is an instrument used to measure the rate of flow of electric current in a circuit. The ammeter must be connected in series (as shown in figure 3.7) if one is interested in measuring the current flowing through a circuit component.

Figure 3.6 An ammeter

The ammeter must have a low resistance so that it does not impede the flow of current. The analogy with an in-line flowmeter in a water circuit can help visualize why an ammeter must have a low resistance, and why connecting an ammeter in parallel can damage the meter.

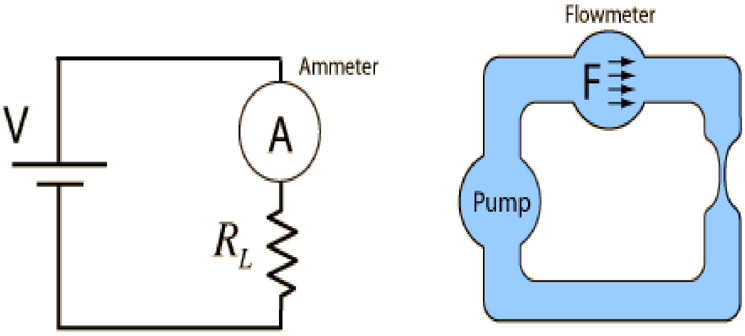


Figure 3.7: Ammeter connected in series

Accessed at: http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

3.6.2.4 Potential difference

The potential difference between two points in a circuit is the amount of work that is done (or energy transferred) when 1 coulomb of charge moves from one end to the other.

V = potential difference in volt (V) W = energy (work) measured in joule (J) Q = charge measured in coulomb (C) 1 volt is therefore 1 Joule per coulomb ($J.C^{-1}$) V = W / Q

3.6.2.5 Voltmeter

A voltmeter (figure 3.8) is an instrument that measures the potential difference between two points in a circuit. It must be connected in parallel (as shown in figure 3.9) and have a high resistance so as to block the flow of current.

Figure 3.8 A voltmeter

In analogy with a water circuit, a voltmeter is like a meter designed to measure pressure difference.

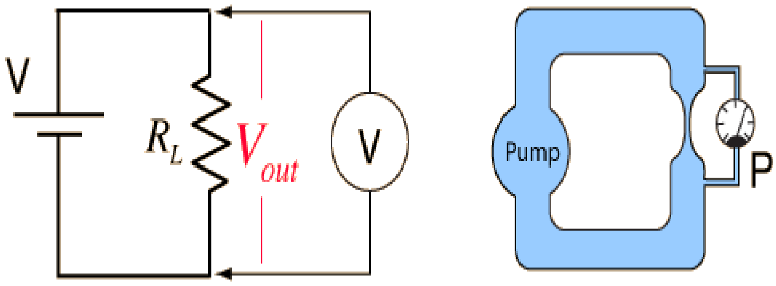


Figure 3.9: A voltmeter connected in parallel

Accessed at: http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

3.6.2.6 Resistance

Resistance is a measure of "how hard" it is to "push" electricity through a circuit element. Resistance can also apply to an entire circuit. When electrons are in motion they have kinetic energy. Due to collisions energy is transferred and the electrons slow down. The resistor heats up and the resistance increases. This is something we experience in our everyday use of electricity when appliances heat up when in use. The unit of resistance is the ohm (Ω) which is defined as a volt per ampere of current.

Factors affecting the resistance:

1. The type of conductor. Resistance **depends on the material the wire is made of**. The more tightly an atom holds on to its outermost electrons the harder it will be to make a current flow.
2. The length of the conductor. Resistance is **proportional to length.**
3. The thickness (cross-section) of the conductor. Resistance is **inversely proportional to cross-sectional-area**.
4. The temperature of the conductor. Resistance **increases with the temperature of the wire**. The hotter wire has a larger resistance because of increased vibration of the atomic lattice.

Accessed at: http://www.cyberphysics.co.uk/topics/electricity/higher_electricity/resistance.htm

The relationship between the current, voltage (potential difference) and resistance in a circuit was discovered by Georg Simon Ohm and it is called Ohm's Law. This relationship is shown in figure 3.10.

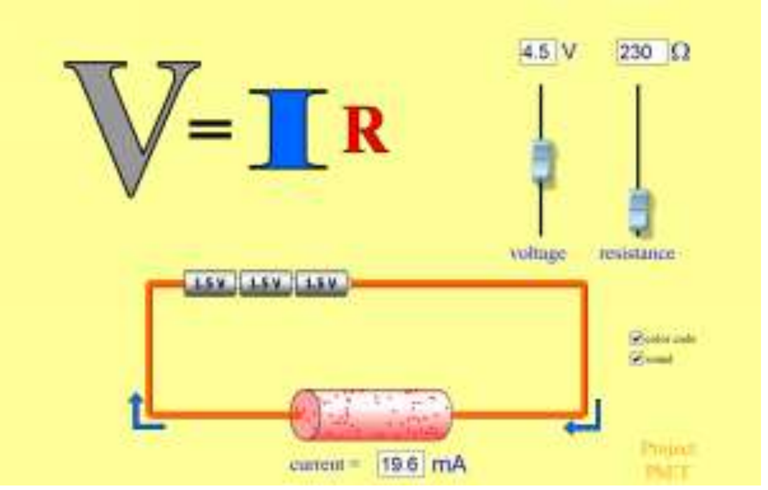


Figure 3.10: Relationship between voltage, current and resistance

Accessed at: http://phet.colorado.edu/en/simulation/ohms-law

3.6.2.7 Ohm's Law

The amount of electric current through a metal conductor, at a constant temperature, in a circuit is proportional to the voltage across the conductor and can be described by:

$$I = V / R$$

I is the current through the conductor, *V* is the voltage across the conductor and *R* is the resistance of the conductor.

The relationship is graphically illustrated in Figure 3.11 for two different conducting wires. The line with the greater gradient (slope) shows a greater resistance.

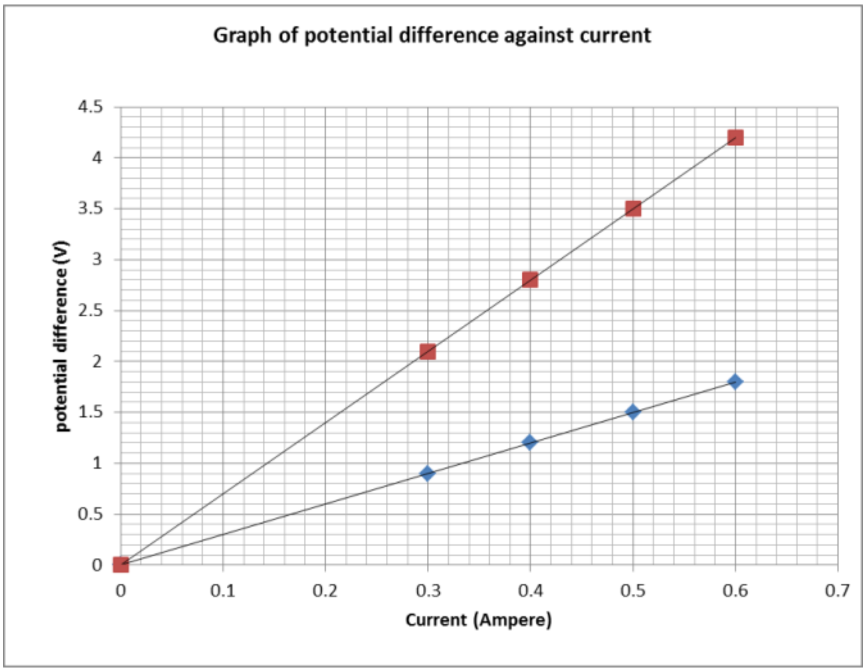


Figure 3.11: Graphical relationship between potential difference and current to illustrate Ohm's Law

3.6.2.8 Resistors in series

The following key concepts are relevant when teaching about series combinations (figure 3.12):

1. The current is the same throughout the circuit as there is no alternative path for the current to flow.
2. The equivalent resistance is the sum of all the resistors:

$$R_s = R_1 + R_2 + \ldots$$

3. The potential difference is divided so that:

$$V_{Tot} = V_1 + V_2 + \ldots$$

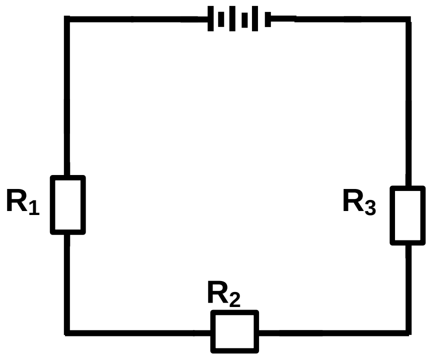


Figure 3.12 A series combination

3.6.2.9 Resistors in parallel

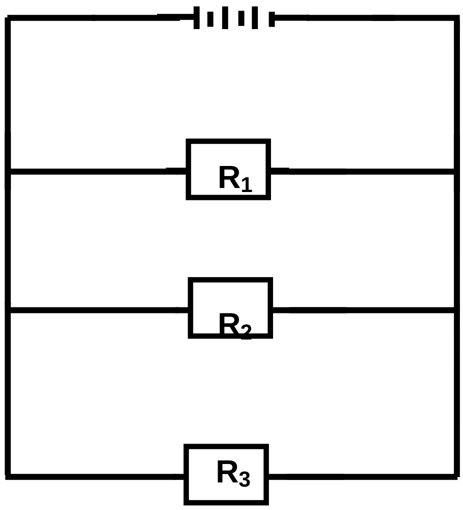


Figure 3.13 A parallel combination

The following key concepts are relevant when teaching about parallel combinations (figure 3.13):

1. The current is divided proportionally:

   $I_T = I_1 + I_2 + \ldots.$

2. The equivalent resistance is given by:

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

3. The potential difference across each resistor is the same:

   $V_1 = V_2 = V_3$

3.7 Pedagogical dimension

Heywood and Parker (2010:14-15) contended that the notion that an individual's knowledge and understanding of the world is constructed rather than transferred has been crucial to the cognitive approaches of the 1980s and 1990s. The focus of teaching and learning has thus been on seeking ways to challenge learners' thinking through scientific inquiry in order to promote their conceptual development when they are actively engaged with appropriate tasks. Vygotsky's socio-cultural tradition embodied within social constructivism considers the environment or context as the most important component within which learning takes place. The individual constructs understanding through various modes of communication and interaction with significant others. Learning in science depends on the extent to which discussion of, and engagement with scientific ideas are encouraged (ibid., p.16). Research evidence also strongly suggests that pre- and in-service teachers often view science teaching as the transmission of factual knowledge. This is in contrast with the role of the teacher expounded within the Vygotskian tradition which advocates an interactive classroom discourse. The ultimate task of the teacher is to provide the necessary scaffolding to mediate scientific knowledge.

The pedagogical strategies advocated to address the content dimension of electric circuits encompass scientific investigations, the use of models and modelling, argumentation, etc. These strategies are outlined below.

3.7.1 Scientific investigations

DeBoer (2006: 17) expounded the view that science is 'a body of richly interconnected observations and interpretations regarding the natural world, and it is a set of procedures and logical rules that guide those observations and interpretations'. Scientists seek to understand the natural world through scientific inquiry which is the general process of investigation that they use. Teachers use scientific inquiry as a teaching methodology in an inquiry-based classroom to promote students' understanding of the principles of science. Student engagement through direct, hands-on experience during scientific investigations also strengthens their understanding of the methods and content of science (ibid., p.19). It can also serve as a means of motivating them and give them a sense of control over their own learning.

Scientific inquiry should not be employed simply as a way of keeping students busy, but it requires intellectual commitment to attain the desired goals and outcomes. These must be carefully designed to stimulate student involvement by providing a balance between prescribing the investigation or being too open-ended. Inquiry teaching is multifaceted and it can be used to accomplish a variety of purposes, the main one being to deepen student understanding of science. Novak and Krajcik (2004: 77) also argued that 'students engage in various activities and develop multiple representations of their understanding as they engage in the extended inquiry science curricula'.

Scientific inquiry refers to the development of process skills and combining it with scientific knowledge, scientific reasoning and critical thinking to develop scientific knowledge (Lederman and Lederman, 2012: 338). A distorted view of scientific inquiry exists which is promoted as the scientific method. The latter can be seen as an algorithm or recipe for success when conducting scientific investigations and is found in most high school textbooks. This research study seeks to develop pre-service science teachers' conceptual understanding of basic current electricity by moving away from this traditional textbook approach. Science investigations are designed with a hands-on and minds-on approach whereby the student must be able to explain whatever phenomena they observe.

The latter point is also motivated by the notion of a big idea. Windschitl et al. (2010: 10) "portrayed big ideas as relationships between some *natural phenomenon* and its *underlying causal explanation*". Heywood (2007: 522) accentuates this when he asserts that:

> There is an important difference between *knowing* about scientific facts and theories and *understanding* how and why a phenomenon occurs. The latter demands a coherent causal explanation for the phenomenon that serves to provide a convincing rationale for observations.

In the study of direct current electricity, for example, the student might observe the brightness of light bulbs in series compared with a parallel combination. The underlying causal explanation entails an understanding of energy transformations in the circuit which is in fact the big idea. Bell, Devés, Dyasi, de la Garza, Léna, Millar, Reiss, Rowell and Yu (2015: 2) argued that reforms of pedagogy in science education are necessary and that inquiry-based learning can lead to a greater depth in understanding. The identification of big ideas in science should be seen as a natural accompaniment to promoting inquiry-based science education.

3.7.2 Models and modelling

Schwarz et al. (2009: 633) define a scientific model as a representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena. Two aspects relevant to this study are appropriated, viz.

- Students *construct* models consistent with prior evidence and theories to illustrate, explain, or predict phenomena.
- Students *use* models to illustrate, explain, and predict phenomena.

(ibid., p.635)

The authors asserted that the pedagogical benefits depend on how students develop models to demonstrate their understanding of a phenomenon. It is relevant to this study since both the notions of sense-making and communication is explored when the students construct their project model in electricity. They develop their understanding (sense-making) during the construction and reach consensus. During the classroom presentation they demonstrate their model and communicate their understanding through explanation of the scientific phenomena (ibid., p.636). Models can be in the form of diagrams, material models, simulations, etc. The research done by Schwarz et al. (2009) also highlights the difficulty of mapping a learning progression for students which go against the grain of normal classroom practice. Students did not see the use of a model as a means to facilitate their own thinking or communicate their understanding (ibid., p. 672).

Heywood and Parker (2010: 39) stated that the use of analogies as a strategy deployed in teaching is that of developing understanding of abstract phenomena. It is used as a pedagogic strategy and a cognitive tool to develop insight. In the study of simple electric circuits it is used to develop a qualitative understanding of concepts that are abstract (ibid., p.40). During a research study of 25 in-service primary teachers three different analogies were applied to simple circuits. These included the blood circulatory system, role-play and a closed water system. The authors concluded that the usefulness of an analogy is largely dependent on whether it resonates with the learner's existing experience (ibid., p.50). They caution that in order to promote teaching and learning in science we should be aware of the possibility of a breakdown in the analogy as a learning opportunity.

Abell et al. (2010: 255) cited Glynn (1991) who stated that analogies involve one concept which is familiar, and constitutes the analogue; the other is the difficult concept that the analogue helps us understand via the mutual similarities. They strongly advocate the use of analogies and models for the prospective science teacher as a means to develop his/her PCK.

3.7.3 Argumentation

Driver, Newton and Osborne (2000: 298) argued that in the teaching and learning of science students should be given opportunities to construct and reconstruct their own personal knowledge through a process of dialogic argument. Aydeniz, Pabuccu, Cetin and Kaya (2012: 1303) stated that argumentation is a reform-based pedagogy which is consistent with what social constructivism espouses, namely that students must share knowledge and construct understandings through dialogue.

Osborne (2007: 179) articulated the following view: "In particular we must break the tie so strongly embedded in the *cultural habitus of teaching science* that the primary task is to persuade students of the validity of the scientific world view – where experiments are performed simply to confirm the theoretical predictions elaborated by the teacher" (my emphasis). He proposed dialogic interaction for the students to construct meaning as they present their arguments with the necessary evidence. When this dialogue is carefully scaffolded by the teacher it can allow the student to work in the zone of proximal development as they internalise their understanding (ibid., p.180). Research has also shown that teaching students to reason and argue also enhances their conceptual learning (Osborne, 2010: 466).

Kim and Hand (2015: 224) maintained that the role of the teacher should shift from traditional practices to inquiry-based practices to encourage dialogue in the classroom. In their study, which was meant to encourage elementary science teachers to implement argumentation, it was found that there is a difference between the teachers' argumentation discourse patterns. They suggested that students who are exposed to a teacher who challenges their claims and explanations are more likely to do the same amongst their peers.

In this research study Berland and McNeill's (2010: 772) argumentative product is used following the basic components of Toulmin's model. The claim is the answer to a question or problem and the evidence is the scientific data that support the claim. The appropriateness and sufficiency of the evidence and reasoning is also examined in terms of its relevance, scientific accuracy, quantity and complexity.

The following section outlines the phases of the research design and how each element of the research is connected to each phase.

3.8 Phases of educational design research

Reeves (2006: 59) has shown four connected phases in the design research process as presented in figure 3.14.

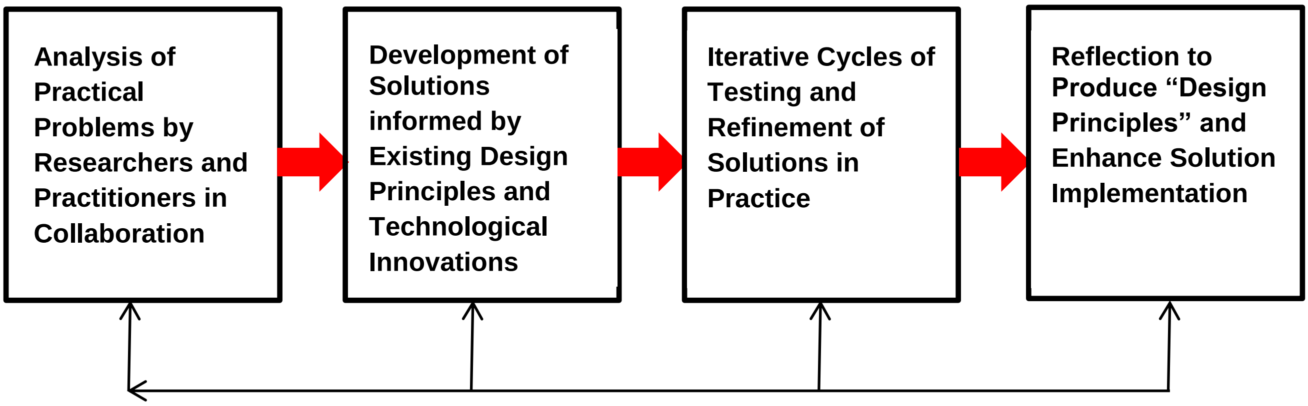


Figure 3.14: Four phases of design research (Reeves, 2006, p. 59)

PHASE 1: Analysis of practical problems by researchers and practitioners

The first step in this phase involves the identification of a significant educational problem. Consultation with practitioners is important as they have insights that are based upon their intimate and practical understanding of the issues. The purpose of the study is to find a potential solution to the problem. Relevant questions are posed by the researchers and practitioners and they decide what data to collect and how it should be analysed. A comprehensive literature review is also done to cite work already completed in the focus area which would serve as the conceptual underpinning of the problem. Relevant research questions then emanate from this which addresses potential gaps in the areas of research. Herrington, McKenney, Reeves and Oliver (2007:4092-4093) have also stated that research questions emerge from the stated problem rather than the stages of design-based research and the focus of the research should remain with the problem area.

PHASE 2: Development of solutions informed by existing design principles and technological innovations

In this phase solutions are proposed that can be implemented in the educational setting such as a classroom or laboratory. These are based on a review of the literature from which suggestions would flow in terms of how to address the problems that have been identified. For example, it could be a suggested learning environment that facilitates learning. Draft principles are drawn up that will guide the design of the intervention. Consideration is then given to how these will be operationalized in the learning environment.

PHASE 3: Iterative cycles of testing and refinement of solutions in practice

The next phase of design-based research is the implementation and evaluation of the proposed solution in practice. It should be noted that design-based research is an approach that uses both qualitative and quantitative methods without an emphasis on isolating variables. Specific objects and processes in specific contexts are studied as ‘integral and meaningful phenomena’ (van den Akker, Gravemeijer, McKenney, & Nieveen, 2006: 5)

Implementation of intervention (First iteration)

Design-based research is iterative by nature so to gauge the success of the intervention and its effect on the problem situation more than one cycle is required. After the first implementation and evaluation, changes are made to the learning environment to further improve its ability to address the problem (Herrington, McKenney, Reeves and Oliver (2007:4094).

Participants

The study takes place within an educational setting in a particular context and as such the participants are drawn from the practice of the practitioner-cum-researcher. They can be students, teachers, support personnel or others within the educational community.

Data collection and analysis

Data may be collected in cycles of several weeks or semesters, or even years and are likely to vary along with the phases. Herrington, McKenney, Reeves and Oliver (2007: 4094) argued that 'data contributing to contextual understanding are more likely to be emphasized in earlier stages of the study; whereas data on prototype characteristics or user reactions are more likely to be collected later on'. The analysis could include techniques appropriate to qualitative and quantitative data. In qualitative analysis the researcher explains the results by describing the major patterns and ideas that emerge from the transcripts and observation notes (Lodico, *et al.*, 2010:165). Content analysis of the data involves coding, categorizing, comparing, and concluding (Cohen, Manion and Morrison, 2007; Mertens, 2009). It can be undertaken with any documents, interview transcriptions, media products and personal interviews. The process of enumeration can then take place whereby the frequencies of codes are counted (Cohen et al., 2007: 474). Quantitative data could be analysed by using statistical methods such as descriptive as well as inferential statistics. It also offers a 'quick, relevant and focused feedback on student performance' (Cohen et al., 2007: 415). All these methods are applied for their utility value to advance the design-based research.

Triangulation makes use of both quantitative and qualitative data to understand the complexity of human behaviour (Cohen et al., 2007: 141) and so that data from one source can enhance and complement data from the other source (Creswell, 2011: 537).

Implementation of intervention (Second and further iterations)

The second and subsequent iterations of the intervention depend on the findings in the first iteration. A description of how the learning environment changed in order to address the problem is provided to give an insight into the iterative cycle of refinement of solutions in practice.

PHASE 4: Reflection to produce "design principles" and enhance solution implementation

After the implementation, evaluation and iteration of the design cycles, the design principles must be shared and published to inform future development and implementation decisions (Herrington & Reeves, 2011: 598). The iterative nature of the refinement is designed to ultimately realise the desired outcomes. Various outputs such as scientific, practical and societal have been proposed in design-based research which sets it apart from other forms of research (Herrington, McKenney, Reeves and Oliver, 2007:4095). These can take the form of evidence-based heuristics, designed artefacts and professional development programmes. McKenney, Nieveen, and van den Akker (2006:77) have defined a set of tenets that relate to each output, namely rigour, relevance and collaboration. They respectively address the standards, beneficial nature to educational practice, and offer meaningful experiences for the participants.

The four phases and the corresponding elements within each phase are summarised in Table 3.2.

Phase	**Element**
PHASE 1: Analysis of practical problems by researchers and practitioners in collaboration	Statement of problem Consultation with researchers and Practitioners Research questions Literature review
PHASE 2: Development of solutions informed by existing design principles and technological innovations	Theoretical framework Development of draft principles to guide the design of the intervention Description of proposed intervention
PHASE 3: Iterative cycles of testing and refinement of solutions in practice	Implementation of intervention (First iteration) Participants Data collection Data analysis Implementation of intervention (Second and further iterations) Participants Data collection Data analysis
PHASE 4: Reflection to produce "design principles" and enhance solution implementation	Design principles Designed artefact(s) Professional development

Table 3.2 The phases and elements within design-based research

3.9 Retrospective analyses

The development of a domain-specific instructional theory during the design experiment can be useful if it allows other researchers to build upon it when used in a different setting (Cobb & Gravemeijer, 2008: 77). The ultimate objective is to improve the learning trajectory of the student in any setting by testing and revising the conjectures. In a design experiment 'it is reasonable to conceptualize the classroom learning environment as an evolving ecology that does not exist independently of the teacher's and the students' activity but is constituted in the course of classroom interactions' (ibid., p.86). Retrospective analyses of the data set seek to place participants' learning and the means by which it was supported in a broad theoretical context. The trustworthiness, repeatability and generalizability of the analysis are important aspects of design experiments.

Trustworthiness is concerned with the reasonableness and justifiability of inferences and assertions that result from a retrospective analysis (Cobb & Gravemeijer, 2008:87). The credibility of the analysis depends on whether it is systematic and open to scrutiny and critique by others. All phases should therefore be well-documented by means of video-recordings, field notes and copies of students' written work to substantiate all claims.

In this study the credibility of the data set is sought through thorough documentation of all interactions in the learning environment. The learning trajectories that are anticipated as well as the actual trajectories are all presented. These include all copies of student assessments, video recordings and transcriptions.

Repeatability refers to the potential of certain aspects of the learning process that may be repeated in a different setting. The idea is that these should be delineated during the retrospective analysis by highlighting the necessary and contingent aspects of the design (ibid., p.89). This is not an advocacy to realise the design in the same way in a different setting, but rather to adapt and modify an instructional sequence in a particular class.

As stated earlier, DBR takes place in a natural setting as opposed to say an experimental research with a control group. Although it is domain-specific, the instructional theory which is generated can be transferred to other local contexts by formulating a hypothetical learning trajectory (Bakker & van Eerde, 2015: 443). All aspects of the design of this study are carefully outlined within each cycle of the teaching experiment which allows for transferability.

Generalizability arises when activities and events in the learning setting are framed as exemplars or prototypes. Cobb and Gravemeijer (2008:89) argued that the value of framing an experiment as a paradigmatic case of a broader class of phenomena shows the importance of generalizability. Cohen, et al. (2007: 135) posited the view that generalizing refers to generalizing *within* specific groups or communities, situations or circumstances validly. When the intention is to give accurate portrayals of the realities of social situations in their natural or conventional settings without manipulating variables or conditions then ecological validity occurs (ibid., p.138). Gravemeijer and Cobb (2008: 45) contended that 'design research aims for ecological validity' so that teachers in other settings may adapt the instructional sequence to their own classrooms. The notion of a 'thick description' is advocated by describing the participants and the teaching- learning situation in detail. Lodico, et al. (2010: 35) emphasised this when they stated that 'thick descriptions involve a comprehensive description of the individual, the social context, and the characteristics of the community, morals, values, and the like'. Repeated trials in different settings also enhance the ecological validity.

In this DBR study the logic of *process oriented explanations* is invoked whereby the event sequence is the envisioned learning trajectory. This comprises the learning activities and shifts in students' reasoning, and the "key point is to establish causality in the trajectory" (Reimann, 2011: 43 – 44). In this manner causality is sought independently of generalizability by looking at the sequence of events and the consequences thereof.

3.10 Ethical considerations

Reimann (2011: 41) has argued that because design research addresses student learning in a substantial manner, there will always be an element of teaching involved. In this study the teacher educator takes on the role of researcher as well during the teaching experiment. It is essential that the researcher be familiar with the proposed envisioned learning trajectory as well as the learning environment in which it must be enacted. There is no conflict of interest as far as I am concerned because the content material remains the same as it would have been enacted in a traditional classroom setting. It is through deeper analysis and reflection of the pedagogical strategies that are adopted that improvements in the learning environment are brought about in order to develop the students' conceptual understanding. However, it must be acknowledged that during the implementation cycles certain tensions arise in terms of wanting to give the correct scientific view while students grapple with different elements of inquiry-based teaching.

3.10.1 Informed consent and confidentiality

Students involved in the study were given an informed consent letter in which the purpose of the study, procedures, potential risks, discomforts, benefits, confidentiality, participation or right to withdraw were outlined. All information, including video recordings, will remain securely saved and no participant will at any stage be identified.

In the following chapter the cycles of the design process are outlined. This includes the different phases of the teaching experiment within each cycle, and how these have been implemented and refined during the different iterations.

CHAPTER 4

PHASES OF DESIGN

This chapter outlines the different phases in the design process and how these were implemented with three cohorts of PSSTs in the second-year of their teacher education studies at university. The three cycles of the formal enactment of the teaching experiment was preceded by a preliminary phase as indicated in chapter 1.

The next section describes the preliminary phase in detail followed by each of the three cycles of the teaching experiment.

4.1 Preliminary phase: Preparing for the teaching experiment

It is important to examine the literature in the domain when considering the problem of teaching direct current electricity to a group of PSSTs. Gravemeijer and Cobb (2006: 19) made the point that the topic under consideration must be problematized from a disciplinary perspective by asking: "What are the core ideas in this domain?" Another key component that emerged from the literature is the notion of a big idea whereby an observed phenomenon must have a causal explanation. Harlen (2010: 3) argued that ''identifying big ideas in science is a natural accompaniment to promoting inquiry-based science education". The teaching of direct current electricity would broadly fall under the concept of conservation of energy.

Some of the main ideas to be dealt with include the following:

- Electric current is a flow of charge.
- In order for these charges to flow there must be a closed circuit in which the battery is the source of energy.

- Energy gets transferred to resistive elements such as light bulbs to produce heat and light energy.
- Resistive elements impede the flow of charge so that more resistors in series would reduce the amount of current. In parallel the total resistance is reduced which increases the total current.
- Students must find the relationship between voltage (V), current (I) and resistance (R) as in Ohm's law.
- Students must investigate the factors that influence resistance.
- Students must apply V, I and R to circuit problems in a quantitative and qualitative manner.

The preliminary phase of the teaching experiment was conducted in 2010 with a group of second-year Natural Sciences students (n=51) enrolled in the B. Ed programme at university. The lessons below describe what was done over four weeks with this group, and it includes my reflections after each lesson.

In terms of the teaching experiment it is important to differentiate between the envisioned conceptual trajectory (ECT) and actual conceptual trajectory (ACT) as termed in this study. The former represents the anticipated concepts that students must learn and understand as well as the skills they must acquire, including the activities involved, while the latter represents their learning and understanding as is evident from their written and verbal assessment tasks.

4.1.1 (a) <u>Lesson 1:</u> ECT

Figure 4.1 A light bulb connected to a cell using one piece of wire.

1. Students are provided with a single piece of conducting wire, a light bulb and one cell. Various possibilities exist to make the bulb glow as shown in figure 4.1
2. This introduces the idea of a closed circuit.
3. The students are thrust into a ''hand-on" and "minds-on" mode. By working within a group they are also encouraged to engage in discussion.

(b) Reflection: ACT

About half the class was able to complete the activity successfully on their own. Others asked questions such as why a second piece of wire is not provided. With a bit of help the whole class got to connect the light bulb correctly. The follow-up discussion highlighted the requirements for electric current to flow as well as defining it as a flow of charge.

What raised my concern at this point was the students' lack of exposure to simple practical tasks. There also appeared to be a reluctance to experiment with the equipment which was a key component of what was intended in the module.

4.1.2 (a) <u>Lesson 2:</u> ECT

The second lesson was designed to extend the students' exposure to working with simple circuits and in a way establish the desired classroom norms. They must continue to work collaboratively and discuss their answers to come up with plausible explanations.

In this task they must connect identical light bulbs as shown in figure 4.2.

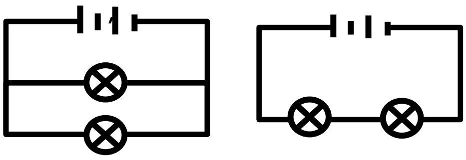


Figure 4.2 Parallel and series connections of identical light bulbs

They must compare the brightness of the identical light bulbs in series with parallel connections. In each case one bulb must be disconnected and they must observe what happens and explain their observations. Each group must write down their answers on an overhead projector transparency sheet which a representative of the group must present to the class.

(b) Reflection: ACT

The students were becoming more comfortable connecting the basic electric circuits. The observations were all correct, but the explanations varied in quality and appropriateness. Important explanations centred on the fact that in series there is an incomplete path when one bulb is removed whereas in parallel there is still a complete path for the current to flow. While some of the students were also unable to explain why the two light bulbs in parallel were brighter than in series, others came up with a plausible explanation. For example, they reasoned analogically that it is like traffic flowing from a single lane into a dual lane when the bulbs are in parallel which makes it easier for the current to flow. This was an important moment in moving towards developing a scientific model which students could apply when dealing with direct current electricity.

4.1.3 (a) <u>Lessons 3&4:</u> ECT

In this double lesson two workstations were set up as shown below. Students were provided with completed circuits and they had to record current strength and potential difference (voltage). They were now introduced to the ammeter and voltmeter as instruments that measure current strength and potential difference respectively. Emphasis is placed on the ammeter being connected in series while the voltmeter is connected in parallel. Reference is also made to the ammeter having a low resistance whereas the voltmeter has a high resistance. The task was completed within the assigned groups.

(b) Workstation 1: ECT

Two identical light bulbs (A & B) are connected in parallel and a third (C) identical one is added in series as shown in figure 4.3.

Make sure that the circuit is complete and record the following observations:

A. The brightness of the light bulbs.
B. The reading on the ammeters.
C. The potential difference across A, B and C (use the multi-meter in position as indicated).
D. The brightness of light bulbs B and C when A is unscrewed (please screw back into position).

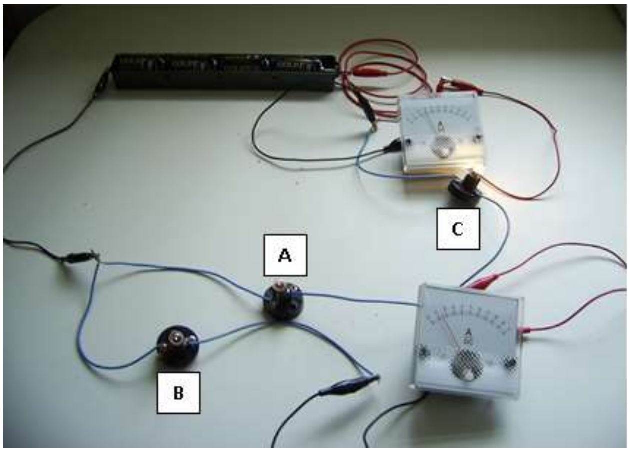
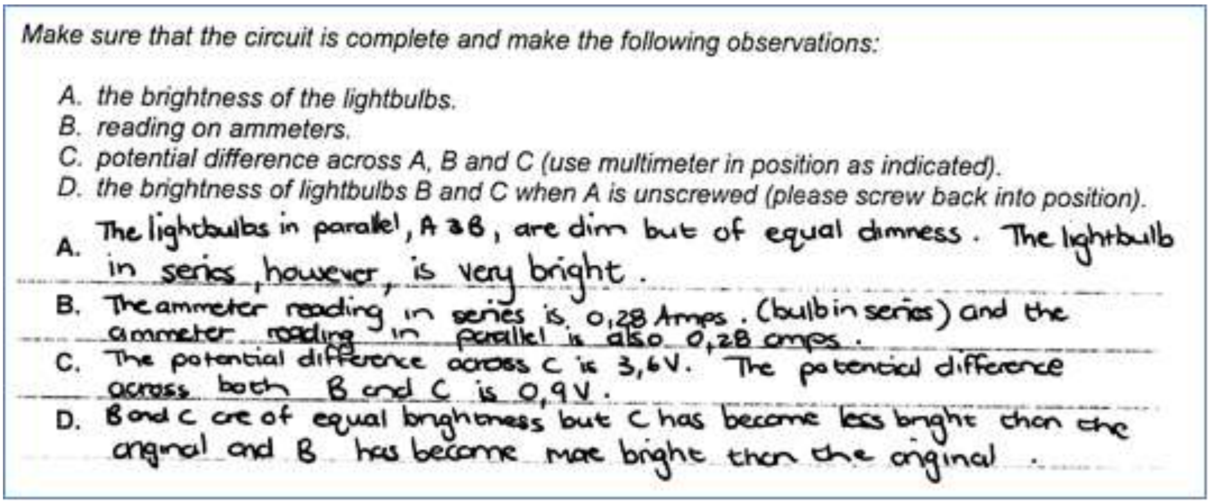


Figure 4.3 Experimental set-up for workstation 1

The main idea embedded within this task is for the students to observe and deduce that the current reading can be linked to the relative brightness of the light bulbs. Further, the current divides in parallel and the voltages are the same across the light bulbs in parallel. When the light bulb is unscrewed the other two light bulbs are in series and have equal brightness.

(c) <u>Reflection:</u> ACT

Most of the observations were recorded correctly except for a few which could be ascribed to the vagaries of the equipment and students' getting used to doing proper readings with the instruments. In most instances this was quite new to them. A typical student response at workstation 1 is shown in figure 4.4.


Make sure that the circuit is complete and make the following observations:

A. the brightness of the lightbulbs.
B. reading on ammeters.
C. potential difference across A, B and C (use multimeter in position as indicated).
D. the brightness of lightbulbs B and C when A is unscrewed (please screw back into position).

A. The lightbulbs in parallel, A & B, are dim but of equal dimness. The lightbulb in series, however, is very bright.
B. The ammeter reading in series is 0,28 Amps. (bulb in series) and the ammeter reading in parallel is also 0,28 amps.
C. The potential difference across C is 3,6V. The potential difference across both B and C is 0,9V.
D. B and C are of equal brightness but C has become less bright than the original and B has become more bright than the original.

Figure 4.4 A student response at workstation 1

(d) Workstation 2: ECT

Two resistors (5 Ω and 10 Ω) are connected in parallel as shown in figure 4.5.

A. Write down the ammeter readings.
B. Record the voltmeter readings across each resistor and across XY.
C. Write down your conclusions with regard to the current strength and potential difference.

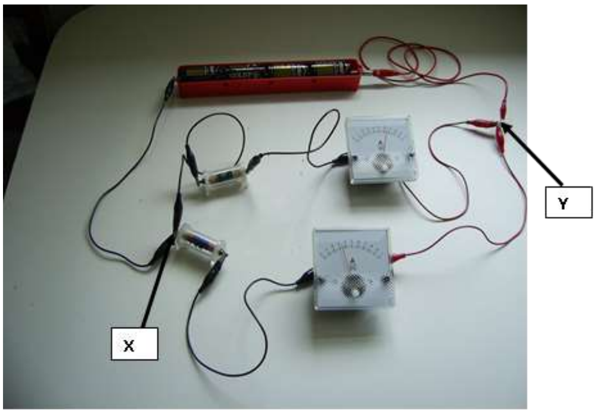


Figure 4.5 Experimental set-up for workstation 2

Students now continue to work with the ammeter and voltmeter. The key ideas within this task are that the current divides proportionally and that the voltages are the same in parallel.

(e) Reflection: ACT

An analysis of the students' answers showed that the majority concluded that the current decreases when the resistance increases while the potential difference remained constant. Some groups concluded that the current divides while two groups correctly explained that the current splits in the ratio 2:1.

4.1.4 (a) Lessons 5&6: ECT

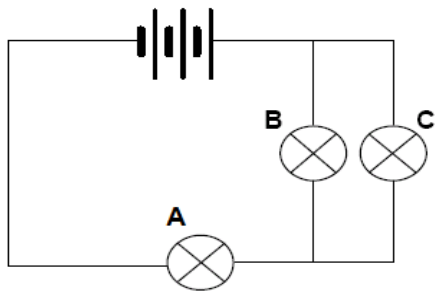


Figure 4.6 Circuit diagram used for MCQ with identical light bulbs

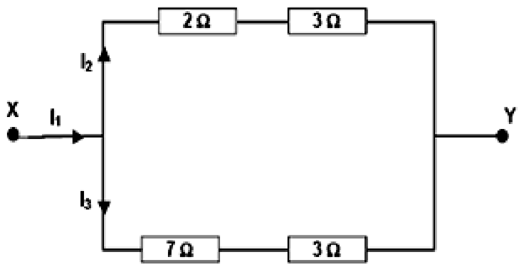


Figure 4.7 Circuit diagram used for MCQ with resistors in parallel

As a follow-up lesson to the previous practical activity the students were given an assessment using multiple-choice questions (MCQs). The two circuit diagrams which closely resembled the set-up at the workstations are shown in figures 4.6 and 4.7. Other questions were also included, but I will reflect on these two only because they were the most problematic for the students.

(b) Reflection: ACT

Only forty percent (40.0%) of the students could correctly state what the brightness of the light bulbs would be once bulb C is removed from the circuit as in figure 4.6. Twenty percent (20.0%) indicated incorrectly that both light bulbs would be brighter. Students were also unable to transfer their experiences from the practical activity to the MCQs. Only thirty percent (30.0%) correctly argued that the current splits proportionally and the voltages are the same across the resistors in parallel as in figure 4.7.

4.1.5 (a) <u>Lessons 7&8:</u> ECT

This practical investigation extends the inquiry-based science advocated through the teaching experiment. Students will be assessed on their process skills such as stating a hypothesis, identifying the variables, graphing, etc. In particular, the students are to establish the relationship between current, potential difference and resistance as in Ohm's law (figure 4.8). This is followed by an investigation to determine the factors that influence resistance.

Nichrome and Eureka conductors (each 0,2 mm diameter) are connected in turn to determine the resistance of each. The apparatus is set up as indicated.

Take voltmeter and ammeter readings to draw a graph. Determine the resistance from the graph.

Use the same set of axes.

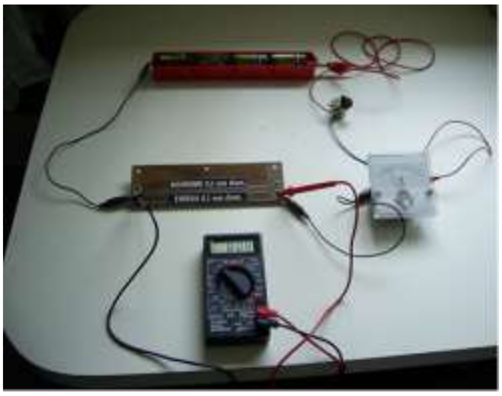
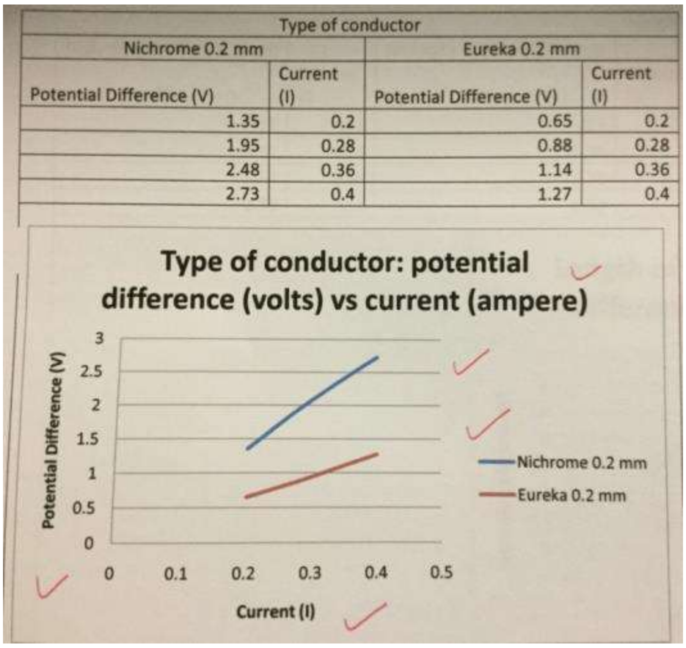


Figure 4.8 Experimental set up to determine Ohm's law

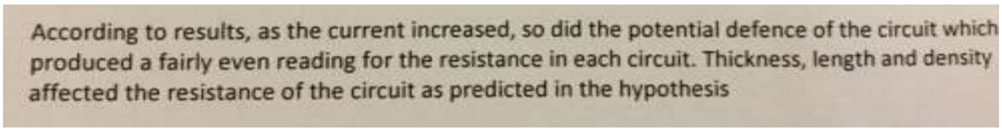
(b) Reflection: ACT

The students scored an average of 73.0% on this assessment task. They were able to tabulate data and draw graphs (figure 4.9) which demonstrated their ability to translate from the experimental mode to other modes. However, they were unable to draw adequate conclusions and interpret the data correctly as shown in figure 4.10.



Type of conductor			
Nichrome 0.2 mm		Eureka 0.2 mm	
Potential Difference (V)	Current (I)	Potential Difference (V)	Current (I)
1.35	0.2	0.65	0.2
1.95	0.28	0.88	0.28
2.48	0.36	1.14	0.36
2.73	0.4	1.27	0.4

Figure 4.9 Typical student tabulation of data & drawing a graph on the science investigation report



According to results, as the current increased, so did the potential defence of the circuit which produced a fairly even reading for the resistance in each circuit. Thickness, length and density affected the resistance of the circuit as predicted in the hypothesis

Figure 4.10 An example of a student's conclusion on the science investigation report

4.1.6 (a) <u>Lessons 9 – 12:</u> ECT

Subsequent lessons included circuit diagrams with parallel and series combinations of light bulbs or resistors. Students had to apply Ohm's law to solve the problems which included quantitative as well as qualitative questions.

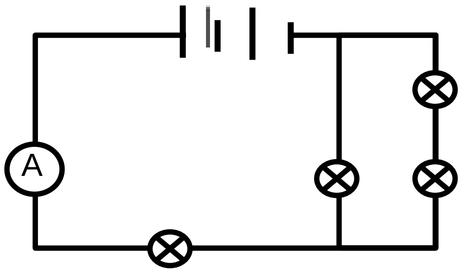


Figure 4.11 A circuit diagram used for problem-solving

Figure 4.11 is an example of the type of circuit diagram which combines parallel and series combinations.

(b) Reflection: ACT

In an assessment which included problem-solving type questions the students scored an average of 53.0%. There was also a significant difference between their scores on this formal test compared with the practical task.

The t-test results are shown in Table 4.1 below:

t-Test: Paired Two Sample for Means		
	Practical investigation	**Test**
Mean	21.4	23.7
Variance	32.8	48.8
Observations	55	55
Pearson Correlation	0.52	
Hypothesized Mean Difference	0	
Df	54	
t Stat	-2.79	
P(T<=t) two-tail	0.0074	
t Critical two-tail	2.00	

Table 4.1 Results of the t-test of the practical investigation and formal test during the preliminary phase

4.2 Overall reflection after the preliminary phase

The idea about using the teaching experiment is to focus on understanding how students learn rather than provide statistical explanations as required by experimental or quasi-experimental research (Gravemeijer and Cobb, 2006: 18). The transformative conjecture –driven teaching experiment in this study proposes a learning trajectory that embraces inquiry-based pedagogy to develop the conceptual understanding of PSSTs in the domain of direct current electricity. The classroom activities and assessments serve as landmarks as the student traverses the terrain that leads to understanding. During the preliminary phase these activities are provisional and could change during subsequent iterations.

A key observation at the start is that the researcher has to take the existing classroom culture into account. Students are used to the traditional didactic approach whereby the lecturer stands in front and delivers the content of the lesson. The challenge is to overcome this by stating upfront what the outcomes are for the module. Once the goals are clearly identified it becomes easier to negotiate various pedagogical approaches. Working with university students makes it much easier. Another significant factor is that the students had different levels of exposure to science at high school – it was therefore a fine balance between finding the levels of cognitive demand without compromising on quality. Using an inquiry-based teaching approach in science affords the teacher an opportunity to balance the content and pedagogy. From a social constructivist perspective it is important to engage the students by building on their prior experiences, and to give them opportunities to discuss and argue as they negotiate their own understanding.

The ultimate aim would be to establish whether students' shifts in reasoning and understanding resulted from the learning trajectories envisioned in this study. The preliminary phase serves as a starting point to identify the key concepts in the domain, formulate assessments to probe understanding and state the processes to be adopted within the theoretical framework. An obvious shortcoming in this phase has been the duration of the interactions with students. There is a definite need to extend it to at least six weeks. The exposure of students to more "hands-on" and "minds-on" science has been very useful. In the next iteration I would provide more opportunities for them to work collaboratively by letting them design a model that incorporates the principles of direct current electricity. It is the explanatory model that they produce through the process of argumentation that would be more important to develop their conceptual understanding.

4.3 THREE CYCLES OF THE TEACHING EXPERIMENT

The sections that follow describe the three cycles of the formal enactment of the teaching experiment with the 2011 to 2013 cohorts of students. Phase 1 is the same for all three cycles.

4.3.1 PHASE 1: Analysis of the problem

> Unless initial teacher education can prepare beginning teachers to learn to do much more thoughtful and challenging work, and unless ways can be found, through professional development, to help teachers to sustain such work, traditional instruction is likely to persist in frustrating educational reform, and reformers' visions are likely to continue not to permeate practice broadly or deeply.
>
> (Ball and Cohen, 1999: 6)

The sentiments expressed in the above quote find common ground with the Department of Higher Education and Training's (2011: 56) minimum set of competences required of newly qualified teachers, one of which is that they "must be able to reflect critically, in theoretically informed ways and together with their professional community of colleagues, on their own practice in order to constantly improve it and adapt it to evolving circumstances". Against a background of curriculum change and the introduction of the Curriculum Assessment policy Statement (CAPS) in South Africa, it is important that teachers are able to adapt to changing circumstances. This implies that they must have a broad set of skills and knowledge about their subject, no matter what the curriculum might be termed.

Heywood (2007) has argued that course provision must address the issue of identifying areas of weakness in student subject knowledge, and finding effective strategies for its development. Research has also shown that student teachers frequently possess ideas about scientific phenomena that differ from current scientific explanation. Botha and Reddy (2011: 258) contended that to attain an understanding of science and the development of scientific knowledge while taking into consideration the needs of diverse groups of learners, teachers will have to display differentiated and integrated knowledge domains to effectively design and guide learning experiences. Kriek and Grayson (2009: 199) also proposed that South African teachers need development along three dimensions: content knowledge, teaching approaches and professional attitudes.

The pre-service science teachers who embark on a four-year study programme to attain a Bachelor of Education (B. Ed) degree are not required to have completed Life or Physical Sciences in Grade 12. This results in a huge content gap as they enter the programme, particularly for those who specialise in Natural Sciences teaching up to Grade 9 in the Senior Phase. The teacher educator is thus faced with a dilemma to address these glaring shortcomings if most students have no real background in science. So there has to be a fine balance to develop their conceptual understanding in science along a continuum which embraces content knowledge and teaching approaches.

In this research study it is proposed that the conceptual understanding of the pre-service science teacher in the domain of direct current electricity may be developed through an inquiry-based teaching approach. This is an attempt to move away from the traditional didactic approach with a strong advocacy of teaching big ideas in science as opposed to delivering a set curriculum which could change at any time. It is also embedded within a framework of social constructivism as it allows the student multiple opportunities to engage with concepts and hence develop their conceptual understanding and knowledge base.

4.3.2 PHASE 2: Developing solutions for classroom setting

(a) Practical activity

Students are given a battery, single piece of conducting wire and a light bulb. They are instructed to make the bulb glow by using only the components that are provided. This activity is completed in groups.

Envisioned conceptual trajectory:

This establishes the fact that a closed circuit is needed for current (electric charge) to flow. The battery provides the source of energy for electric charge to flow. It also exposes the students to basic circuit components and sets the tone for practical hands-on activities. They also work collaboratively and generate a lot of excitement when the bulb glows.

This activity is followed by a discussion of different models (Shipstone, 1985: 36) as shown in Figure 4.12 below.

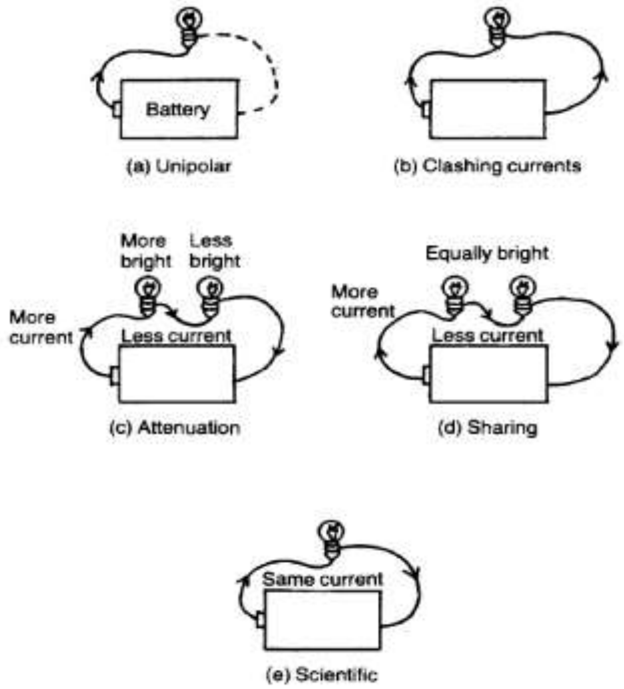


Figure 4.12   Conceptual models for current in simple electric circuits

Envisioned conceptual trajectory:

The idea is to address students' alternative frameworks and provide the accepted scientific model. It also translates the invisible (charges and energy) into something more perceptible such as the brightness of the light bulb.

(b)   Models and analogies

The following analogies and models are introduced to explain the concept of current in an electric circuit. Students are then allowed to come up with their own analogies. Students are introduced to the bicycle chain analogy in which the pedal provides the energy which is transferred via the chain to the back wheel where energy is transformed.

The water circuit model (figure 4.13) uses a pump to represent the battery, a turbine to represent the light bulb, and water pipes to represent connecting wires.

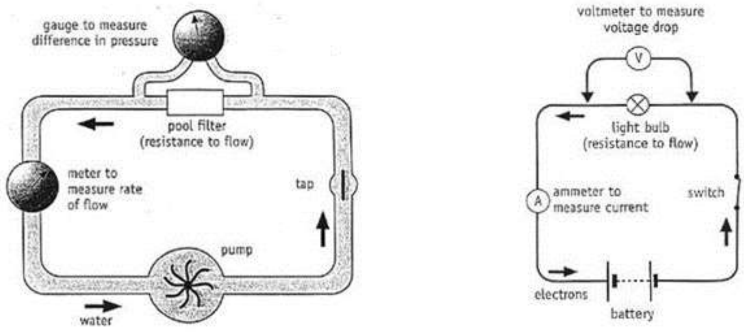


Figure 4.13 The water circuit model

Envisioned conceptual trajectory

"The use of models, metaphors and analogies is vital in developing students' understanding of electric circuits because to explain what we observe in a circuit (e.g. the lighting of a bulb) involves using science ideas about things we cannot see, such as energy and electrons."
http://www.education.vic.gov.au/school/teachers/teachingresources/ (Accessed February 2011).

(c) Scientific investigation:

Determine how the cross-section, length and type of conductor influence resistance using the experimental set-up as in figure 4.14.

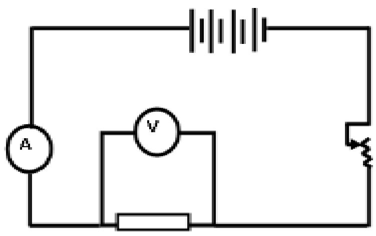


Figure 4.14 Circuit diagram for scientific investigation

Envisioned conceptual trajectory:

Students are provided with the necessary equipment to conduct the investigation in groups. They are given assistance to connect the components correctly as in the accompanying diagram. They are also exposed to an ammeter and voltmeter which must be connected in series and parallel respectively.

The following skills are assessed (see rubric in Addendum A): Formulation of hypothesis, investigation design, data collection, recording and display of data, analysis and conclusion.

These skills also test the students' ability to translate from one mode of representation to the other and to write a scientific report of their findings.

(d) Electricity project:

Groups of two or three students were required to build a working model which illustrated the principles of electricity that they learnt in class. The model had to be demonstrated (see Figure 4.15) and explanations of the concepts underpinning the model had to be given to the class.

Figure 4.15 A typical project model

The students were given the following components: Battery holder; switch; electrical motor; light bulb holders; light bulbs and conducting wires. They could use any cheap material to build the model.

Envisioned conceptual trajectory:

The collaboration in groups ensured a collective effort which tapped into the diverse abilities of the members. They had to ensure that the components were correctly connected and functioning. The creativity of the project and their explanations were assessed (see rubric in Addendum B). This is an attempt to promote the students' argumentation skills as they had to reason conceptually and provide a justification for any claim that they made relating to the model.

(e) Practical activity

Students are given two identical light bulbs, two cells and conducting wires. They must connect the bulbs in series and parallel and observe the brightness in each case. One bulb must be unscrewed in each case and the students must record their observations. An explanation is required for both scenarios as shown in figure 4.16.

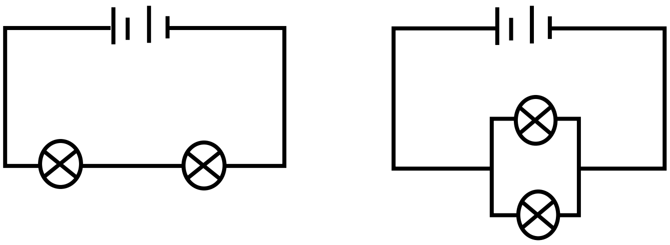


Figure 4.16 Two identical light bulbs connected in series and parallel respectively

Envisioned conceptual trajectory:

This practical activity is meant to reinforce the fact that in series the current strength is the same so that the bulbs are equally bright. The total voltage is also divided across each bulb. When one bulb is removed there is no complete circuit so that the other bulb does not glow any longer. Each bulb in parallel has the same increased voltage which explains why they are equally bright, but brighter than in series. When one bulb is removed the other continues to glow because there is a continuous pathway for the current. In reality there is a slight increase in the brightness due to the lost volts in the battery being less.

(f) Simulations

Students are asked to look at the simulations on electricity at http://phet.colorado.edu and to consider how it can be integrated in a lesson? The following simulations on Ohm's law and a Circuit Construction were completed:

(i) Ohm's Law

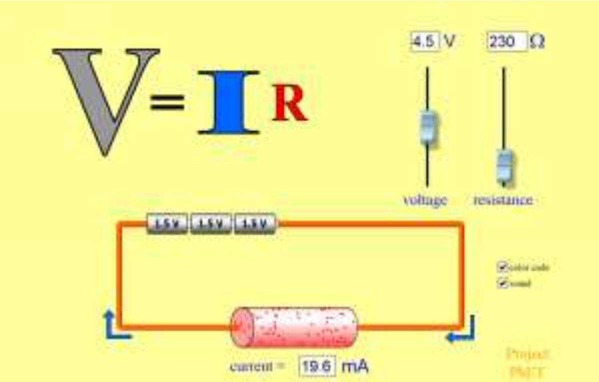


Figure 4.17 Simulation of Ohm's law

http://phet.colorado.edu/en/simulation/ohms-law

See how the equation form of Ohm's law relates to a simple circuit. Adjust the voltage and resistance, and see the current change according to Ohm's law. The sizes of the symbols in the equation change to match the circuit diagram as in figure 4.17.

(ii) Circuit Construction Kit (DC Only), Virtual Lab

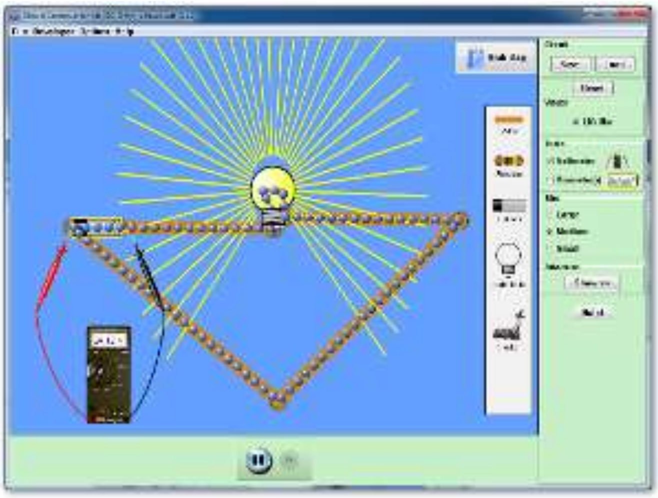


Figure 4.18 Simulation of circuit construction

http://phet.colorado.edu/en/simulation/circuitconstructionkitdcvirtualab

Build circuits with resistors, light bulbs, batteries, and switches and take measurements with laboratory equipment like the realistic ammeter and voltmeter as in figure 4.18.

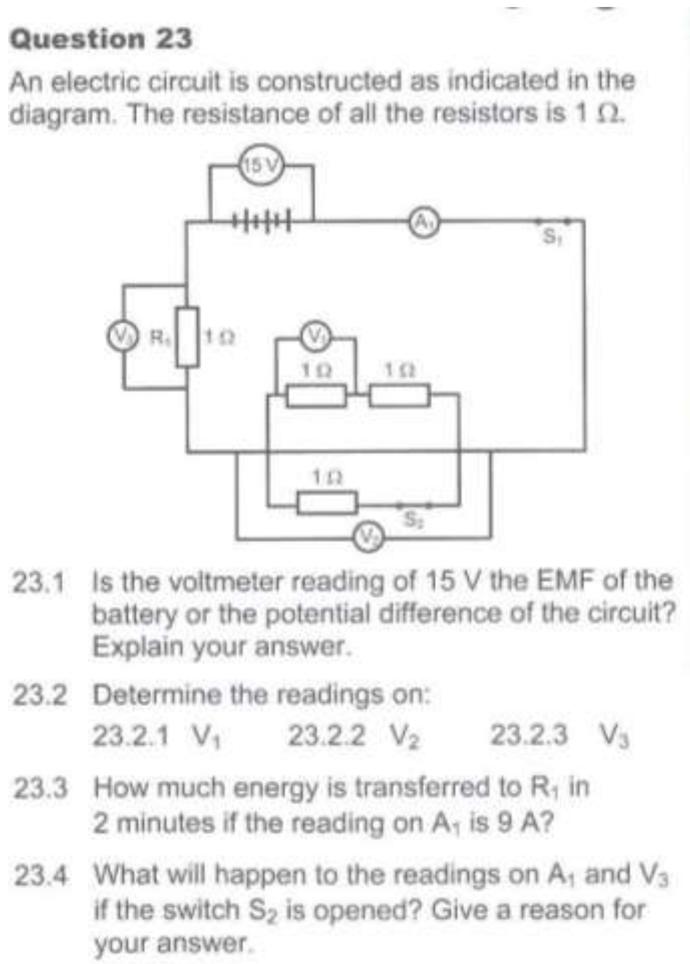
Envisioned conceptual trajectory

Simulations provide an extension of the multimodal representation framework in science. It provides a visual representation of the phenomena and can be quite a powerful tool. For example, students can see the charges moving as the bulb lights up. In the case of Ohm's law, the size of the symbols change as one variable changes.

(g) Problem-solving

The students have to be engaged with problem-solving in electric circuits in order to apply their conceptual understanding. The following is a typical example (figure 4.19) which the students have to understand to expand their content knowledge.

<u>Example 1:</u>



Question 23

An electric circuit is constructed as indicated in the diagram. The resistance of all the resistors is 1 Ω.

23.1 Is the voltmeter reading of 15 V the EMF of the battery or the potential difference of the circuit? Explain your answer.

23.2 Determine the readings on:
23.2.1 V_1 23.2.2 V_2 23.2.3 V_3

23.3 How much energy is transferred to R_1 in 2 minutes if the reading on A_1 is 9 A?

23.4 What will happen to the readings on A_1 and V_3 if the switch S_2 is opened? Give a reason for your answer.

Figure 4.19 Example of an electric circuit for problem solving

Envisioned conceptual trajectory

This example reinforces what happens in a series and parallel circuit. In series the current is the same throughout the circuit and the total voltage is divided, whereas in parallel the current is divided and the voltages are the same. Students have to apply the formulae to solve the problem.

Example 2:

Refer to the circuit diagram and calculate/write down:

(i) Voltmeter readings V_2 and V_3.
(ii) Ammeter reading A_1.
(iii) Resistance of R_1, R_2 and R_3.
(iv) The voltage of each cell.

Assume that the battery has negligible internal resistance.

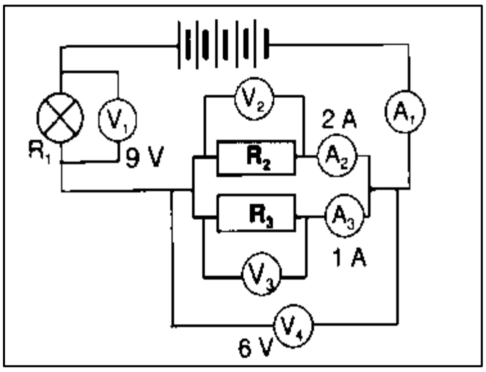


Figure 4.20 Example of an electric circuit integrating series and parallel resistors

Envisioned conceptual trajectory

The example in figure 4.20 integrates a series and parallel combination of resistors. It also reinforces the concepts of current, potential difference and resistance which pertains to the two types of combinations.

4.3.3 PHASE 3: Iterative cycles of testing and refinement

4.3.3.1 Cycle 1 – implementation with 2011 cohort

(a) Participants

The participants are 63 second-year level Natural Sciences students (11 males and 52 females) enrolled in a Bachelor of Education (B. Ed) programme at university. Scott and Usher (2011: 79) stated that “convenience sampling comprises choosing an unrepresentative sample by selecting respondents because it is convenient for the researcher”. The students are a convenient sample because they were readily available (Henry, 1990; Patton, 2002; Lodico, et al. 2010; Creswell, 2011) and they are a captive audience (Cohen et al., 2007). The researcher must also not attempt to generalize the results beyond the given population because there are limitations to the sample (Mertens, 2009; Creswell, 2011).

(b) Data collection

As outlined in chapter 3, designed-based research employs quantitative and qualitative methods of data collection by studying student records, videos and classroom assessments. The use of quantitative and qualitative data is also a feature of mixed method designs (Teddlie & Tashakkori, 2009) and can provide a better understanding of the research problem (Creswell, 2011). The pragmatic parallel mixed methods design is utilised in this study and "is one in which qualitative and quantitative data are collected and analysed to answer a single study's research questions" (Mertens, 2009: 298). The data are collected independently of each other.

Scott and Usher (2011: 107) have argued that "researchers need to understand both the context of the activities they were observing and how the data about these activities were collected" in order to understand the constructs used by participants. The data collection takes place over a period of 6 weeks during the presentation of the unit of direct current electricity. During the second week students do the scientific investigation of the factors that influence the resistance of a conductor. The session allows them 90 minutes to complete their data collection. They submit a scientific report a week later which is assessed according to a rubric with a focus on process skills such as hypothesising, graphing, analysis and interpretation, etc. The marks and each process skills category is captured in Microsoft Excel® for all 63 students.

During the final week they present their project model in groups of two or three. This is captured on video and assessed with a rubric which looks at the functioning of the model, creativity and the students' explanation. The marks are captured in Excel and all the presentations are transcribed for later analysis of the students' argumentation product. The final assessment test on electricity follows after the 6 weeks. The questions include multiple-choice questions, problem-solving as well as multimodal translation type questions. The tests are assessed according to a marking memorandum and the marks are captured in Excel and the students' responses on each question are categorised as well for data analysis.

It must be emphasised that DBR strives for ecological validity by not manipulating variables in order to give "accurate portrayals of the realities of social situations in their own terms" (Cohen et al., 2007: 138).

(c) Data analysis

Descriptive statistics is used to present the data in a summarised form and also show the distribution which may be normal, skewed to the right (positive) or to the left (negative), either flat, bell-shaped or thin (kurtosis) (Scott and Usher, 2011; Creswell, 2011). The mean is the arithmetic average, the median the midpoint of the distribution of scores, the mode the measure of central tendency (the score obtained by the greatest number of people), and the standard deviation gives an indication of how adequate the mean is as a statistic (Mertens, 2009; Cohen et al., 2007). Inferential statistics is used to make comparisons and the t-test is used in particular in this research study for correlated samples where two sets of scores are available for the same group of people (Mertens, 2009: 406). Inferences and predictions are made based on the data gathered (Cohen et al., 2007: 504) and the t-test is used to discover any statistically significant differences between the means of two sets of scores.

The qualitative data for the research study was obtained from the transcriptions of the video recordings of the project presentation. Hesse-Biber and Leavy (2006:347) maintained that this process is interactive and engages the researcher with the research material. The data was transferred into Excel according to Berland and McNeill's (2010: 772) argumentation product categories outlined in chapter 3 (section 3.7.3). Data reduction occurs as part of the data is selected for coding if they conceptually "hang together" (Mertens, 2009: 425).

(d) Quantitative analysis of data of three assessment tasks

A detailed table of the results obtained in each assessment task, viz. scientific investigation, project model presentation and electricity test is presented in Addendum C. A bar graph of the average percentage obtained in the three assessments is shown in Figure 4.21. While the students did poorly in the test, a closer look at the descriptive statistics (Table 4.2) gives a better idea of the distribution of the data. The mean and median are almost the same for the test. The median of 38, which is already a failing mark, means that 50.0% of the students fall below this mark. In order to answer the research questions, a more detailed analysis of the questions on the test follows later.

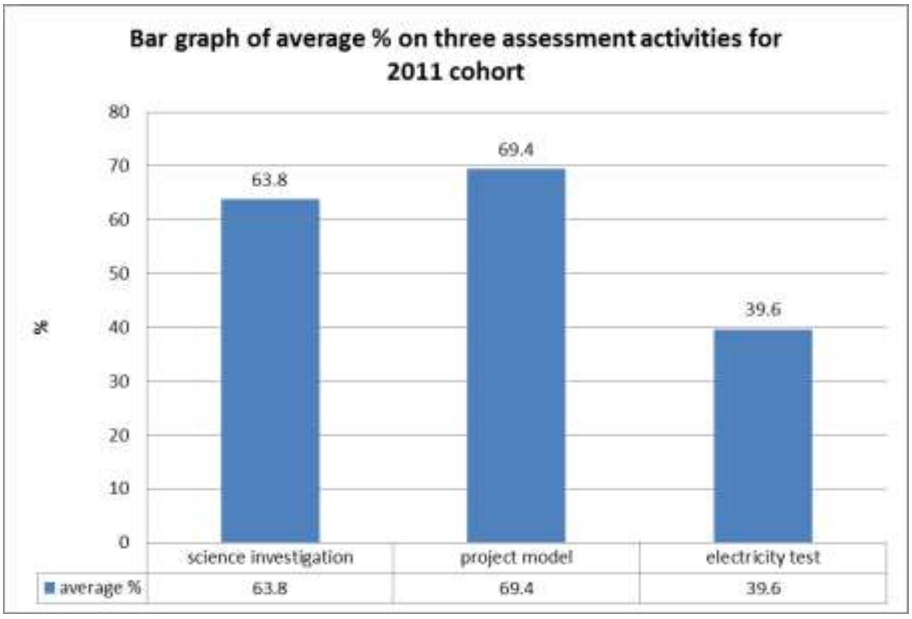


Figure 4.21 A bar graph of the average % on the three assessment tasks for the 2011 cohort

(e) Descriptive statistics for the 2011 cohort

Science investigation		Electricity project		Test	
Mean	63.8	Mean	69.4	Mean	39.6
Standard Error	2.7	Standard Error	2.0	Standard Error	2.2
Median	68	Median	70	Median	38
Mode	63	Mode	78	Mode	32
Std Deviation	21.2	Std Deviation	15.6	Std Deviation	17.6
Sample Variance	449.0804	Sample Variance	242.0553	Sample Variance	308.8
Kurtosis	1.020853	Kurtosis	4.824087	Kurtosis	-0.073481756
Skewness	-0.74982	Skewness	-1.24183	Skewness	0.655237082
Range	100	Range	98	Range	74
Minimum	0	Minimum	0	Minimum	10
Maximum	100	Maximum	98	Maximum	84
Sum	4033	Sum	4311	Sum	2494
Count	63	Count	63	Count	63

Table 4.2 Descriptive statistics of three assessments for the 2011 cohort

(f) Analysis of t-test results for the 2011 cohort

t-Test: Paired Two Sample for Means		
	Science investigation	**Electricity project**
Mean	64.0	68.4
Variance	449.1	242.1
Observations	63	63
Pearson Correlation		0.235383
Hypothesized Mean Difference		0
Df		62
t Stat		1.512945
P(T<=t) two-tail		0.135375
t Critical two-tail		1.998972

Table 4.3 t-test statistics for science investigation and project model for the 2011 cohort

The mean score on the science investigation (M = 64.0) was lower than the mean score on the project model presentation (M = 68.4) as shown in Table 4.3. However, this difference was not statistically significant, t (62) = 1.51, p = 0.07 (p > 0.05). It would seem that there is no difference between the students' conceptual understanding on the science investigation compared with the project model presentation. There also appears to be a slight relationship between the scores as the correlation of 0.14 indicates.

t-Test: Paired Two Sample for Means		
	Science investigation	**Test**
Mean	64.0	39.6
Variance	449.1	308.8
Observations	63	63
Pearson Correlation		0.409406
Hypothesized Mean Difference		0
Df		62
t Stat		-9.11044
P(T<=t) two-tail		4.81E-13
t Critical two-tail		1.998972

Table 4.4 t-test statistics for science investigation and test for the 2011 cohort

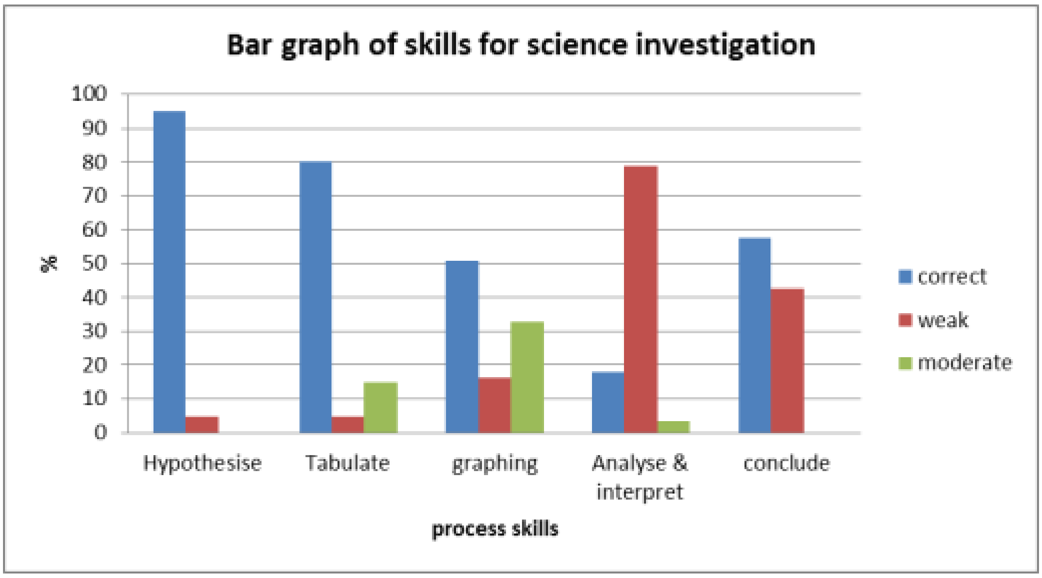
The mean score on the science investigation (M = 64.0) was greater than the mean score on the electricity test (M = 39.6) as shown in Table 4.4. This difference was statistically significant, $t(62) = -9.11$, $p < 0.05$. It would seem that there is a significant difference between the students' conceptual understanding on the scientific investigation compared with the electricity test.

t-Test: Paired Two Sample for Means		
	Electricity project	**Test**
Mean	68.4	39.6
Variance	242.1	308.8
Observations	63	63
Pearson Correlation		0.148971
Hypothesized Mean Difference		0
Df		62
t Stat		-10.5661
P(T<=t) two-tail		1.7E-15
t Critical two-tail		1.998972

Table 4.5 t-test statistics for project model and test for the 2011 cohort

The mean score on the project model presentation (M = 68.4) was greater than the mean score on the electricity test (M = 39.6) as shown in Table 4.5. This difference was statistically significant, $t(62) = -10.57$, $p < 0.05$. It would seem that there is a significant difference between the students' conceptual understanding on the project model presentation compared with the electricity test.

(g) Analysis of science investigation results for the 2011 cohort



	Hypothesise	Tabulate	graphing	Analyse & interpret	conclude
correct	95.1	80.3	50.8	18	57.4
weak	4.9	4.9	16.4	78.7	42.6
moderate	0	14.8	32.8	3.3	0

Figure 4.22 Bar graph of process skills on scientific investigation for the 2011 cohort

The analysis of students' process skills reveals that the process skills such as hypothesising and tabulating are well developed as the bar graph data in Figure 4.22 show. A typical student response is also shown in figure 4.23 as evidence of this. The skills that require higher cognitive levels such as graphing and analysis and interpretation (78.7%) are found lacking. A large percentage of the students are also unable to draw adequate conclusions based on their findings during the scientific investigation.

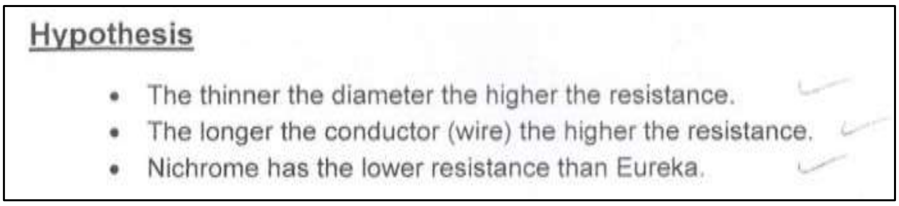
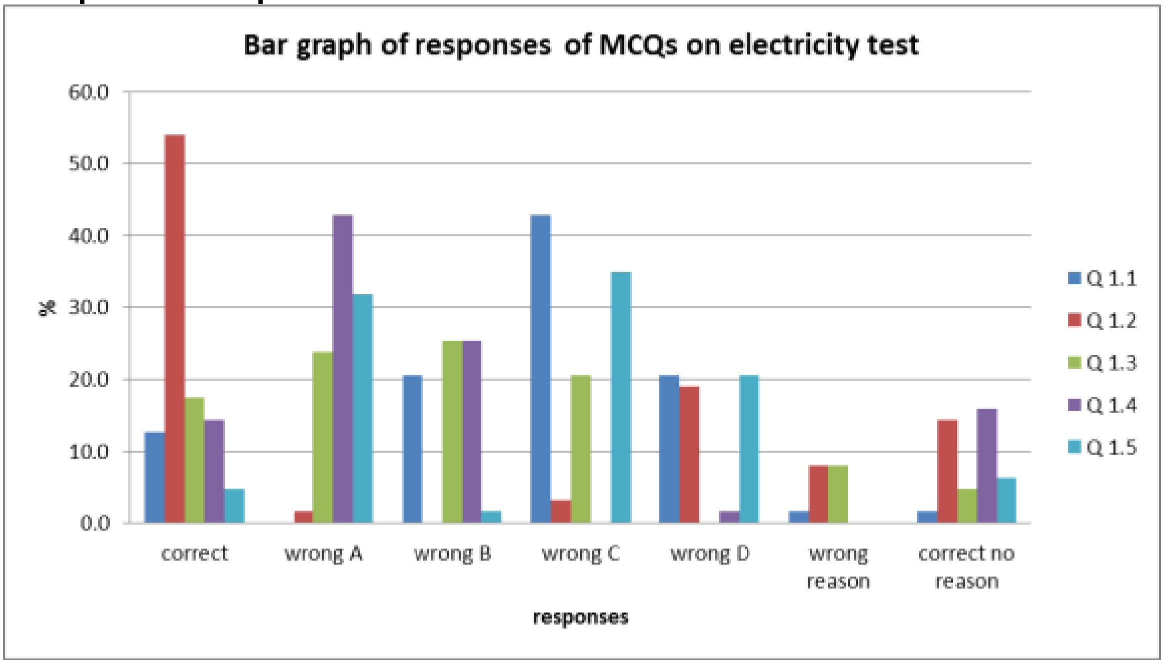


Figure 4.23 A typical student response showing formulation of a hypothesis with the 2011 cohort

(h) Analysis of electricity test results for the 2011 cohort

The test and conceptual trajectory as well as the marking memorandum for each question are presented in Addendum D.

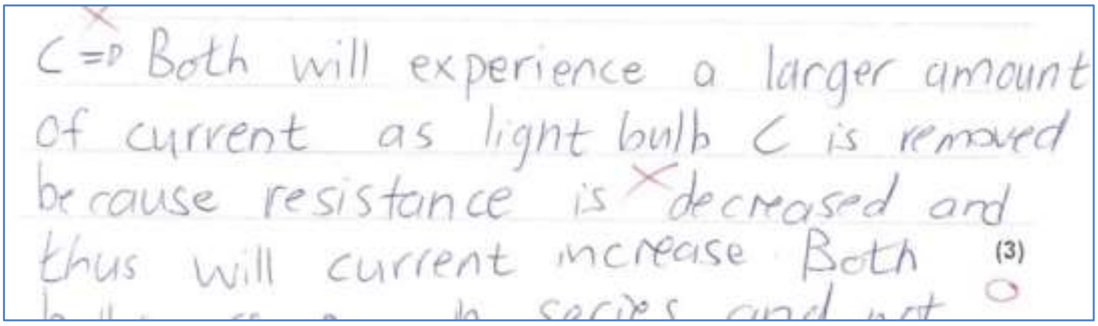
Multiple-choice question with reasons



	Q 1.1	Q 1.2	Q 1.3	Q 1.4	Q 1.5
Correct	12.7	54.0	17.5	14.3	6.3
wrong A	0.0	1.6	23.8	42.9	31.7
wrong B	20.6	0.0	25.4	25.4	0.0
wrong C	42.9	3.2	20.6	0.0	34.9
wrong D	20.6	19.0	0.0	1.6	20.6
wrong reason	1.6	7.9	7.9	0.0	0.0
correct no reason	1.6	14.3	4.8	15.9	6.3

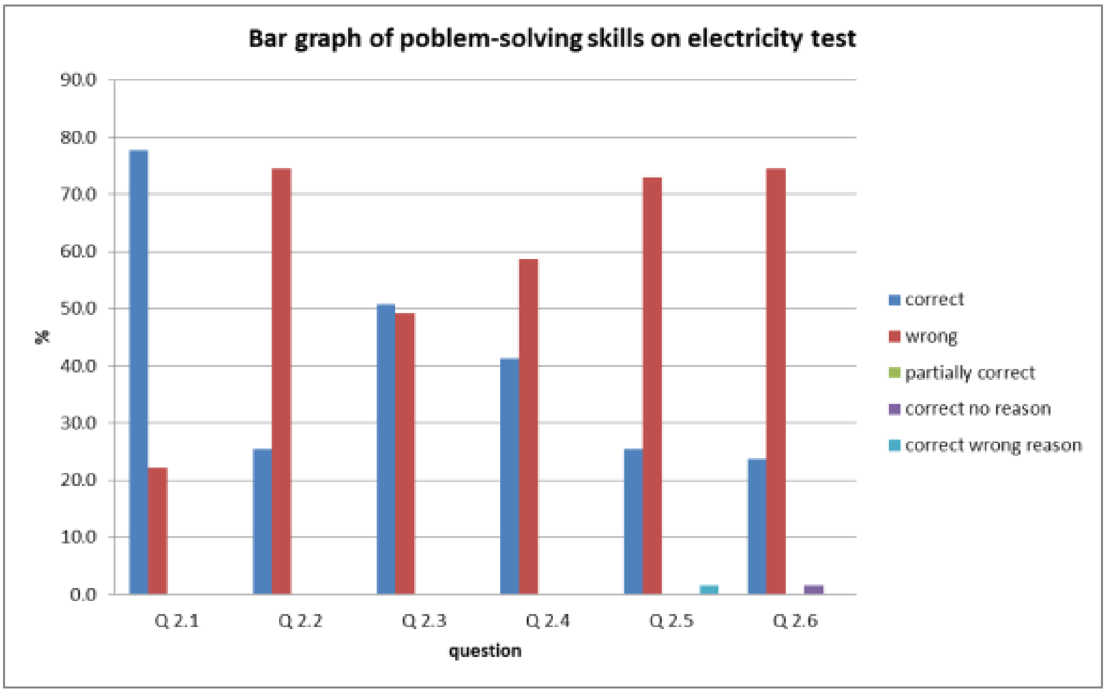
Figure 4.24 Bar graph of responses on MCQs on electricity test for the 2011 cohort

Only question 1.2 had a percentage of correct responses which exceeded 50.0% with 14.4% of the students not giving a reason for their correct answer as shown in Figure 4.24. This was in fact a relatively straightforward question. Question 1.5 had the lowest percentage (6.3%) of correct responses, but the same percentage correct with no reason provided. The 42.9% of students who chose the answer C on question 1.1 appear to not have benefited from the practical exposure to this scenario during class. Figure 4.25 is an example of a student's answer to this question. Question 1.4 tested the basics about current and potential difference on a parallel combination with 42.9% of students missing the latter when they incorrectly responded with A as their answer.



4.25 A student's answer to question 1.1 for the 2011 cohort

Problem-solving question



	Q 2.1	Q 2.2	Q 2.3	Q 2.4	Q 2.5	Q 2.6
Correct	77.8	25.4	50.8	41.3	25.4	23.8
Wrong	22.2	74.6	49.2	58.7	73.0	74.6
partially correct	0.0	0.0	0.0	0.0	0.0	0.0
correct no reason	0.0	0.0	0.0	0.0	0.0	1.6
correct wrong reason	0.0	0.0	0.0	0.0	1.6	0.0

Figure 4.26 Bar graph of problem-solving skills on electricity test for the 2011 cohort

Students are able to do straightforward problem-solving as in question 2.1 which 77.8% got right as shown in Figure 4.26. On question 2.2 they again had a problem (74.6% incorrect) with the split current on a parallel combination. Only 41.3% could correctly determine the EMF of the battery in question 2.4. The last two questions required qualitative reasoning and the students showed that this is an area of poor conceptual understanding on their part. Figure 4.27 shows the poor reasoning of a student on question 2.5.

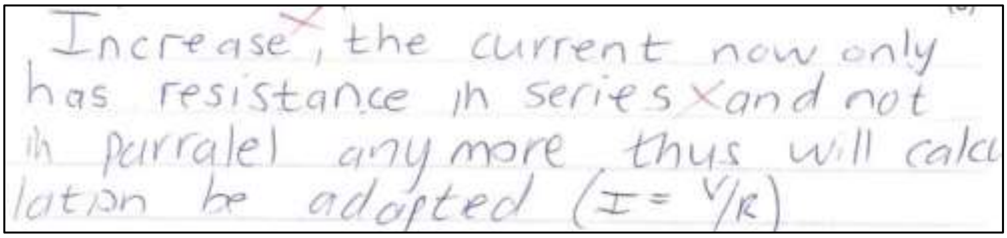
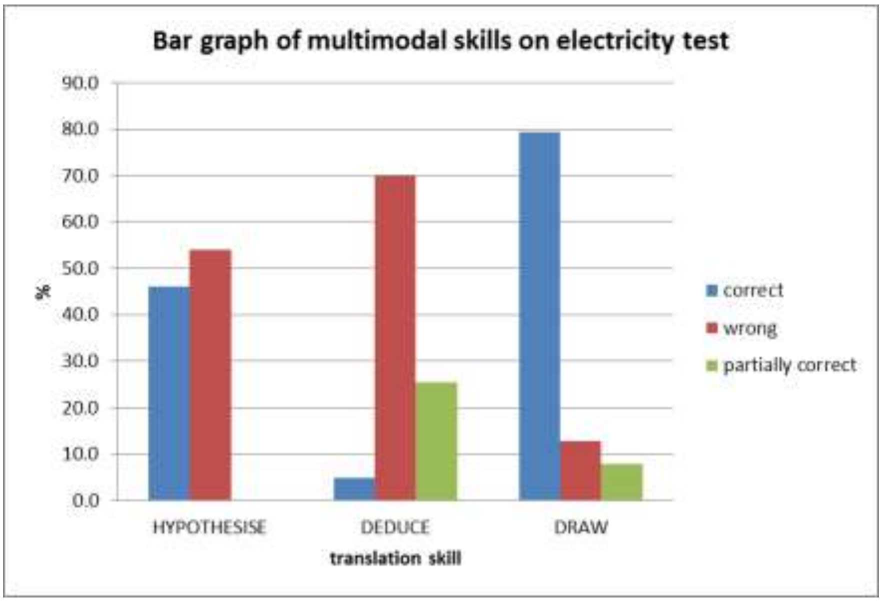

Increase, the current now only has resistance in series and not in purralel any more thus will calcu lation be adopted (I = V/R)

Figure 2.27 A student's response to question 2.5 for the 2011 cohort

Multimodal question



	Q 3.1	Q 3.2	Q 3.3
correct	46.0	4.8	79.4
wrong	54.0	69.8	12.7
partially correct	0.0	25.4	7.9

Figure 4.28 Bar graph of multimodal translation skills on electricity test for the 2011 cohort

Although the students were exposed to a scientific investigation in class, this question was poorly answered as the data in Figure 4.28 show. The majority of students (54.0%) were unable to do a translation from a graph to formulate a hypothesis while 69.8% could not make the correct deductions from the graph. The students were able to do a diagrammatic representation of the investigation which almost 80.0% of them got right as illustrated in Figure 4.29.

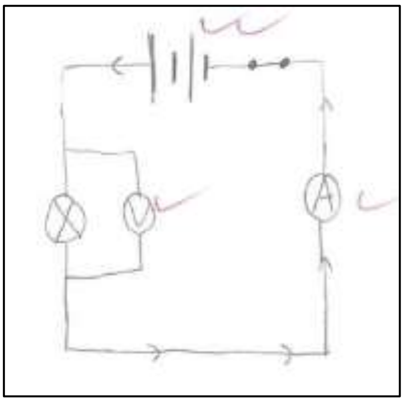
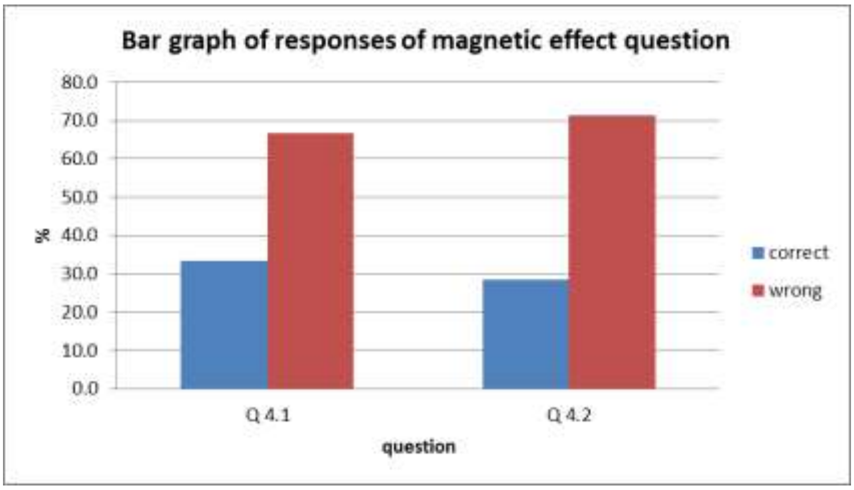


Figure 4.29 An example of a translation activity from an experiment to a diagram for the 2011 cohort

Magnetic effect question



	Q 4.1	Q 4.2
correct	33.3	28.6
wrong	66.7	71.4

Figure 4.30 Bar graph of responses to magnetic effect question on electricity test for the 2011 cohort

This question was very poorly answered as shown in figure 4.30 with the majority of the students being unable to recognise a simple magnetic field pattern for a straight current-carrying conductor. Figure 4.31 shows typically how a student is unable to apply the right-hand wire rule. This activity was completed as an inquiry-based practical investigation in class as well.

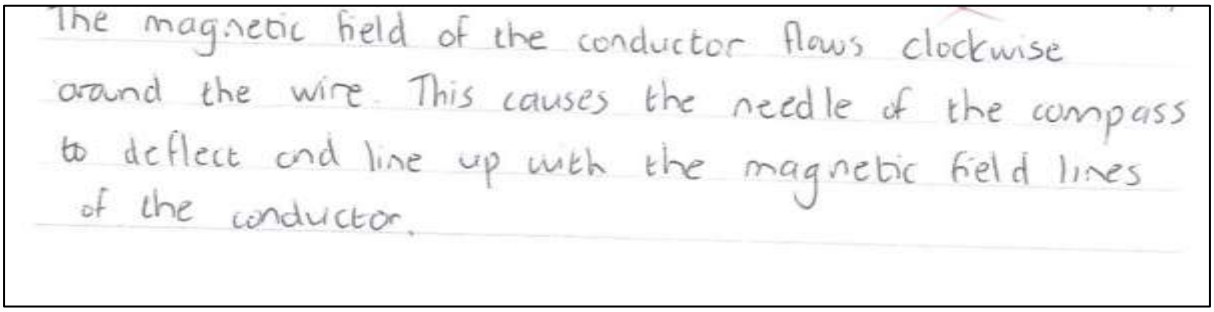

The magnetic field of the conductor flows clockwise around the wire. This causes the needle of the compass to deflect and line up with the magnetic field lines of the conductor.

Figure 4.31 A student's answer to an application of the right-hand wire rule.

(i) Qualitative analysis of project model presentation for 2011 cohort

Table 4.6 Berland and McNeill's (2010: 772) argumentation product categories for the 2011 cohort

Claim *Answer to a question or problem (design a working project model to apply principles of current electricity)*	Evidence *Scientific data/observations that support the claim (a working model)*	Reasoning *Articulates the logic why the evidence supports the claim*	Appropriateness *Evidence and reasoning are relevant to the problem and scientifically accurate to support claim*	Sufficiency *Quantity and complexity of evidence and reasoning can convince an audience of the claim*
When you close the switch, which means if you put it on, then the battery gives energy to all the components in the circuit and the motor then begins turning, as you can see, and the lights now begin to glow.		The reason for the current that flows is that it is connected from positive to negative and we chose the method because such a scientific method connection allows it to flow from positive to negative and work.	Appropriate evidence, but inaccurate reasoning to justify the claim.	Sufficient with low degree of complexity
This is our circuit. It has been designed in a bedroom type of yes. So that's our creative side and the battery is inside the drawers over here so that you can't see it. Ok, so we'll just show you how it switches on quickly. Ok, there you go. Everything is on. It's working.		The two batteries we are using is our circuit supply of the energy source. The two light bulbs over here are connected in parallel which allows equal amount of energy to be applied in both of the batteries. It also means that there is an equal brightness in both the batteries. The LED light is connected also in parallel but over the motor. The reason for this is the LED takes up, if it's not connected in parallel over the circuit it will take up all the energy of the batteries, which then means that the motor won't run and the two light bulbs won't run.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim
What we did we connected the battery to a switch so we could turn the power on. We used the two lights bulbs and we put them in series. Then the motor we put in parallel and that's in parallel to the LED. The top two are in parallel and the bottom one is in series to the light bulbs.		The power on indicates the flow of current with the use of a LED, as you can see there. Current flows from the battery into another LED, into the lights, around and back to the battery. So the positive flows to the LED, to the motor then both out into the battery	Appropriate evidence, but inaccurate reasoning to justify the claim.	Sufficient with low degree of complexity

Firstly we have here a series connection, from this side down. You also need to take note that the motor is now moving very fast. As soon as I connect another component, such as a light bulb, in parallel, the other components, like the motor, will run slower.		In the series the resistance is much more. Then the potential difference between this component and this component it's the same. Because the current must now be shared. So the resistance decreases in the parallel connection and the current strength increases on the components that are in parallel connection.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim
So when the train's going to come past automatically the lights and the bells go on. So we used the motor and a Zambuck lid to make the bell. And the lights are in parallel so that, I'm just going to turn this bottle quickly, so that if one light fuses there's still a light warning the people that there's a train coming along. So there the boom comes down, and when it comes down it makes the LED light up to tell the motorists to stop.		then on this side to explain polarity, how when a current flows in the opposite direction to the initial flow, the motor will spin in a different direction. It completes the circuit with the LED. Here it explains a series connection because the LED is just in a simply series with a battery and that's polarity and how current flows in a different directions causes the magnetic field to work in the opposite direction so the motor turns in different directions.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim
You need a closed circuit and an energy source for energy to flow. This circuit is a closed circuit when the switch is on the right and it is off when the switch is on the left. We decided to connect the light bulbs in parallel.		From the representation of the circuit you can see that the circuit is closed because there are no gaps in the circuit. The battery serves as the energy source. There is therefore a flow of conventional energy in the circuit, in other words the current flows from positive to negative. The reason for this is that the one light bulb will continue to shine if the other one is screwed out and it will also shine brighter. You can also now hear a difference in the speed of the motor. A parallel circuit divides current while the potential difference remains the same.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim

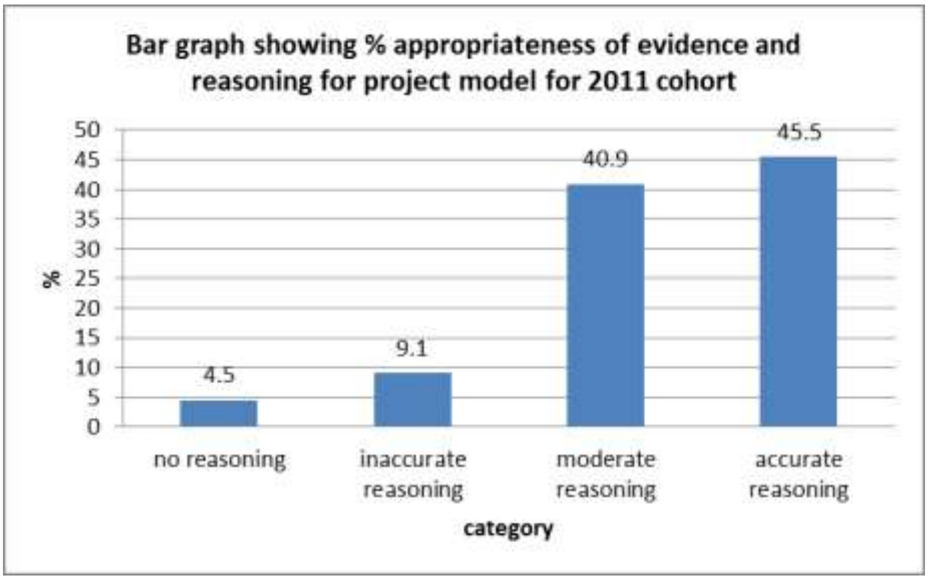
We made a conventional circuit that moves from positive to negative, the current moves from positive to negative. And we have two light bulbs connected in parallel with each other. There are two light bulbs in series together with the motor. We used the switch to basically switch the circuit from the one series circuit to the other series circuit.		We can put one on and the other – while other one is off and then if they are apart they are in series with the fan. So it isn't connected here for the reason that if it was connected would it run at all times because the switch doesn't go on and off, it just switches the circuit over to the other one.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
The components we used for the circuit are two light bulbs, a battery, switch, LED a motor. It is connected in series		The current does not split because it is connected in series and the lights shine at equal levels. And it flows from negative to – positive to negative. The circuit goes to the motor and then the power from the motor goes to the one light bulb and then the power from the light bulb goes to the LED and then from the LED to the next light bulb. So it is one long circuit. Like, nothing splits.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
The only thing I am going to say about that is this is an alternating current so they will explain later what is about. And then when you switch this one on, the motor here and then this bulb, this one, they are on.		We have decided to connect our circuit in parallel so that there will be more than one path along which current flow in, in a circuit. For instance if, if one bulb fuse in the circuit the other bulbs can still function, unlike in, in series connection where as one bulb fuse the other one cannot function.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim
We have a conventional circuit, which means that current flows from positive to negative. And, yes we have a switch and parallel connection and series connection.		If it is in parallel the other one can still work, and these two in series – if you take it out then the other one dies. So it's just a representation that if one, say, fuses in series then the rest won't work. But in parallel the rest will still work. And yes, another reason why it doesn't work well is we used very thin wire, which means that the current – agh there is more resistance so the current doesn't flow very strongly, there is less current.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim

The person is now in the house so the lights shine now. Then as soon as someone breaks in, they come in, the one door moves open and the other door opens and the LED shines to then tell you ok there are people in the house. And then the lights go off.		The light bulbs are connected in parallel so that the one can shine even if the other one is broken or something, so that both can still go off for if the vagrants now come in.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
We used three lights because there must be a lot of light on an aeroplane. Um, the three lights with the motor are connected in parallel. The LED is connected in series. It's that red light that shows there is an aeroplane in the sky.		So that an equal amount of power can go everywhere. Also if one blows there will still be light on the aeroplane.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
What we have here is a roulette table that spins and lights up. We used two 1.5V batteries connected in parallel.		We connected it in parallel so this is less resistance. So now the lights are powered at the same time as well as the roulette table. And if it was in series then if there was one mistake then all of them would be influenced.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
Everything is connected with the motor into the bed. The simple concept is that it turns around. Basically the way we connected it was in two ways, series and parallel.		Operating components being the light bulbs and the motor's connected in parallel. And then the rest is connected in series, that being the battery and the switch to the operating components.	Appropriate evidence and no reasoning for claim	Insufficient with no justification provided for the claim
LED is connected in series with the battery. Unfortunately it draws a lot of the power because the battery is a bit flat. And this light bulb and the motor are parallel with the rest of the circuit in series with each other. And this light bulb is parallel with the rest of the circuit.		If I take this one out, then there is greater power in the fan and these light bulbs are significantly stronger. If I turn this one back then you will notice that the motor becomes a great deal weaker. If I turn this out, this one becomes a great deal stronger.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim

We connected the two bulbs in series, the two identical light bulbs. And in our first observation we didn't use the motor. And when we switched on the switch the bulbs shined brightly. the motor used more of the energy from the battery so the light bulbs is dim.		Like our explanation for the bulbs turning off or being dim was that the motor acts as a resistor in the circuit because it uses, it uses direct current. Therefore, all the current flows from the bulbs all the way to the motor because it uses more electricity. Therefore that is why the bulbs turn off. And we also used the, the formula for current that says the resistance is inversely proportional to the current flow. That is why the bulb here and the motor is, uses more electricity in series.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim
We connected the lights in parallel. See we've connected the battery in series and I think the motor is also in series.		Obviously so that if he loses one eye, the other eye will still work. The current obviously moves from the positive terminal of the battery to the negative terminal of the battery and the current only works if there is a closed circuit and a power source.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim
We connect this in series. The switch here and the lights off, and the motor is, is off still. When you connect it in parallel, the bulbs in parallel, one bulb lights off when sometimes maybe it fuses. And the other one lights off.		But if it was in series then this other bulb when it fuses then the other one fuses too. But when it's in parallel then the other one works because the current is flowing. And then when you connect the motor it generates but then the two bulbs goes off.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim
This is our circuit. It has a motor in and then it has a parallel light, or this is parallel, the whole thing, but in one circuit it has two lights in series and then that light is parallel to them.		There you can now see the Volts sent out from the battery go through two circuits and the Volts, the amount of Volts that goes through the circuit don't divide. The same amount goes through both circuits. Because there are two lights will it naturally be weaker because two lights on one street will make it weaker than one light on one street. Then, because that light is connected in parallel with the series light, if the series light is turned off, turned out, then a current will still flow through so, because a parallel connection doesn't influence the current that goes there.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim

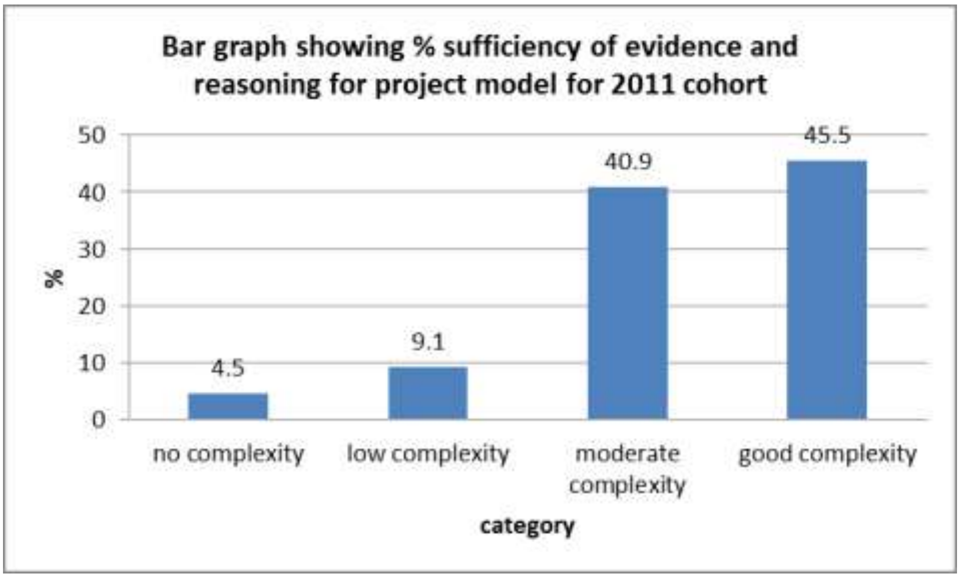
Our current is connected in parallel. If you turn the switch on then one can see the manner it is connected in parallel shows us how bright the lights are and that the LED light works as well as the fan. And the current strength is equal.		If it is in parallel it is equal. If it is connected in series then it would use more energy. Then the battery will run out quicker.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
What we did is we connected the circuit in parallel. You can see that the light bulbs are equally bright.		The current is distributed evenly throughout the circuit.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
In our circuit we have three circuits in one. So here is our power source. So, here if I connect it there this light will go on first. If I turn on here then both lights will burn. Here is our second switch that like shortens the second circuit. As soon as I take it out the fan goes on but the lights will go off		Because the power follows the shortest path first. but it will burn dimmer as it has a larger current to flow through. ... because we only have a 3V battery and the fan draws more than the power of the two together and then it flows through.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim

Students were able to present working models of electric circuits by working collaboratively in groups of three. These models integrated what they had learnt in class as is evident in Table 4.6. This constituted the evidence of their claim in the argumentation framework. The appropriateness (i.e. relevance and scientific accuracy) and sufficiency (i.e. quantity and complexity) of the evidence and reasoning were found lacking. It was found that only 40.9% and 45.5% of students used moderate to accurate reasoning respectively when explaining their model. This implies that a large proportion demonstrated poor argumentation skills by failing to substantiate their claims adequately. Likewise, the complexity of their arguments was also weak. The quantification of the qualitative data is presented in Figures 4.32 and 4.33 below.



	% of projects
no reasoning	4.5
inaccurate reasoning	9.1
moderate reasoning	40.9
accurate reasoning	45.5

Figure 4.32 Bar graph of % appropriateness of evidence and reasoning for the 2011 cohort



	% of projects
no complexity	4.5
low complexity	9.1
moderate complexity	40.9
good complexity	45.5

Figure 4.33 Bar graph of % sufficiency of evidence and reasoning for the 2011 cohort

(j) Overall reflection after cycle 1 of the teaching experiment

The longer duration (6 weeks) during the implementation of cycle 1 allowed much more to be accomplished in terms of inquiry-based activities. In particular, the students were able to present their projects which demonstrated the principles of electricity. The students were also introduced to simulations in addition to doing the practical “hands-on” investigations themselves. It was anticipated that this would deepen their understanding of the basic concepts of electricity.

Providing opportunities for the students to develop their process skills seem to be bearing fruit, but there are areas of concern that still need to be addressed. For example, the majority of students can formulate a hypothesis and tabulate data when conducting a scientific investigation. However, translating the data into a graphical representation, analysing and interpreting the data are still areas of concern. Drawing conclusions based on the evidence of the investigation is also an area of weakness. In relation to the students’ project presentation the evidence varied in quality and appropriateness. From the perspective of affording students a chance to demonstrate their qualitative understanding and reasoning, it was evident that not many of them are able to present cogent arguments based on the principles of direct current electricity.

While the idea had been to expose the students to more inquiry-based science teaching of direct current electricity, it would appear that their problem-solving ability is still lacking. They are able to do easy quantitative problems but not more cognitively demanding problems. Their lack of qualitative reasoning ability alluded to above is also evident in the written test. What is disconcerting is that specific concepts that were done practically in class were poorly answered on the test. For example, the magnetic effect of a current-carrying conductor was demonstrated and explained but the majority of the students could not explain the concept in the test. In the next cycle I would want to address these shortcomings.

4.3.3.2 Cycle 2 – implementation with 2012 cohort

(a) Participants

The participants are 60 second-year level Natural Sciences students (12 males and 48 females) enrolled in a Bachelor of Education (B. Ed) programme at university.

(b) Data collection

The data collection also takes place over a period of 6 weeks during the presentation of the unit of current electricity. During the second week students do the scientific investigation of the factors that influence the resistance of a conductor. The session allows them 90 minutes to complete their data collection. They submit a scientific report a week later which is assessed according to a rubric with a focus on process skills such as hypothesising, graphing, analysis and interpretation, etc. The marks and each process skills category is captured in Microsoft Excel® for all 63 students.

During the final week they present their project model in groups of three. This is captured on video and assessed with a rubric which looks at the functioning of the model, creativity and the students' explanation. The marks are captured in Excel and all the presentations are transcribed for later analysis of the students' argumentation product. The final assessment test on electricity follows after the 6 weeks. The questions include multiple-choice questions, problem-solving as well as multimodal translation type questions. The tests are assessed according to a marking memorandum and the marks are captured in Excel and the students' responses on each question are categorised as well for data analysis.

(c) Data analysis

Descriptive statistics is used to present the data in a summarised form and also show the distribution of the data. Inferential statistics is used to make comparisons between groups and the t-test is used to discover any statistically significant differences between the means of two sets of scores for the same group of students.

The qualitative data for the research study was obtained from the transcriptions of the video recordings of the project presentation. The data was transferred into Excel according to Berland and McNeill's (2010: 772) argumentation product categories outlined in chapter 3. Data reduction occurs as part of the data is selected for coding. Content analysis is undertaken and the process of enumeration can then take place whereby the frequencies of codes are counted. Triangulation of both quantitative and qualitative data is then done.

(d) Quantitative analysis of data of three assessment tasks

A detailed table of the results obtained in each assessment task, viz. scientific investigation, project model presentation and electricity test is presented in Addendum E. A bar graph of the average percentage obtained in the three assessments is shown in Figure 4.34. The students did poorly in the test (40.9%) and had a good average for the project model (79.3%), but a closer look at the descriptive statistics (Table 4.7) gives a better idea of the distribution of the data. The median of 35.0 on the test, which is already a failing mark, means that 50% of the students fall below this mark. In order to answer the research questions, a more detailed analysis of the questions on the test follows later.

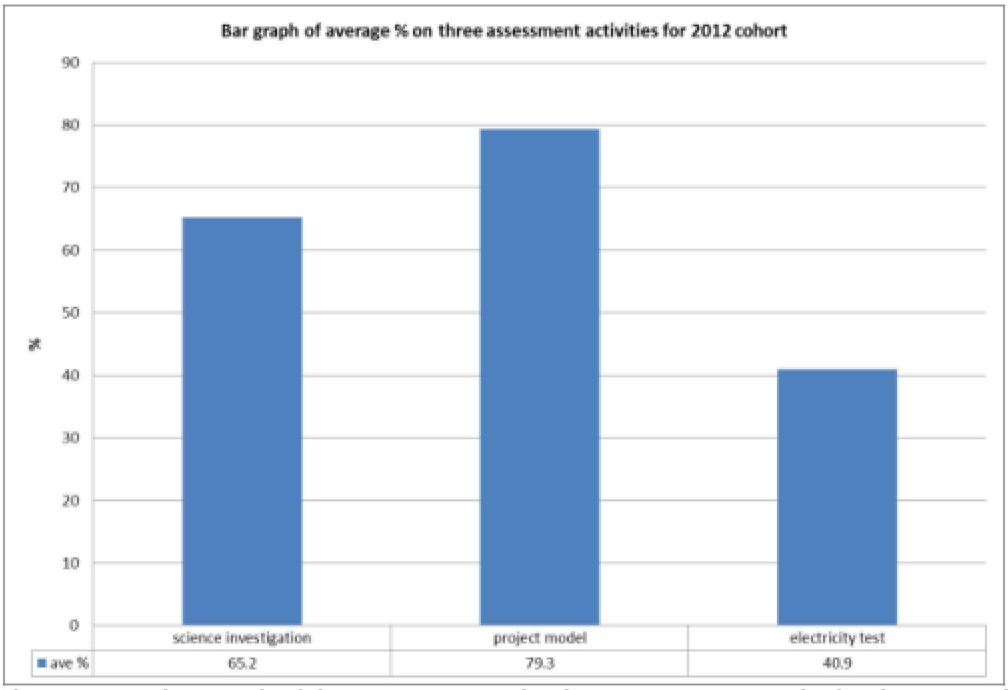


Figure 4.34 A bar graph of the average % on the three assessment tasks for the 2012 cohort

(e) Descriptive statistics for the 2012 cohort

Science investigation		Electricity project		Test	
Mean	65.2	Mean	79.3	Mean	40.9
Standard Error	2.2	Standard Error	1.0	Standard Error	2.3
Median	67.5	Median	80.0	Median	35.0
Mode	56.3	Mode	80	Mode	25
Standard Deviation	16.97116	Standard Deviation	8.042525	Standard Deviation	17.71852
Sample Variance	288.0204	Sample Variance	64.6822	Sample Variance	313.946
Kurtosis	-0.48561	Kurtosis	-0.60758	Kurtosis	-0.61161
Skewness	-0.52339	Skewness	-0.11736	Skewness	0.653778
Range	63.75	Range	30	Range	70
Minimum	27.5	Minimum	62.5	Minimum	12.5
Maximum	91.25	Maximum	92.5	Maximum	82.5
Sum	3911.25	Sum	4755	Sum	2452.5
Count	60	Count	60	Count	60

Table 4.7 Descriptive statistics of 3 assessments for the 2012 cohort

(f) Analysis of t-test results for the 2012 cohort

t-Test: Paired Two Sample for Means		
	Science investigation	**Electricity project**
Mean	65.2	79.3
Variance	288.0	64.7
Observations	60	60
Pearson Correlation	0.0344	
Hypothesized Mean Difference	0	
Df	59	
t Stat	-5.88	
P(T<=t) two-tail	2.05233E-07	
t Critical two-tail	2.00	

Table 4.8 t-test statistics for science investigation and project model for the 2012 cohort

The mean score on the science investigation (M = 65.2) was lower than the mean score on the project model presentation (M = 79.3) as shown in Table 4.8. This difference was statistically significant, $t(59) = -5.88$, $p < 0.05$. There is a significant difference between the students' conceptual understanding on the science investigation compared with the project model presentation. There also appears to be no relationship between the scores as the correlation of 0.03 indicates.

t-Test: Paired Two Sample for Means		
	Science investigation	**Electricity test**
Mean	65.2	40.9
Variance	288.0	313.9
Observations	60	60
Pearson Correlation	0.5265	
Hypothesized Mean Difference	0	
Df	59	
t Stat	11.15	
P(T<=t) two-tail	3.7441E-16	
t Critical two-tail	2.00	

Table 4.9 t-test statistics for science investigation and test for the 2012 cohort

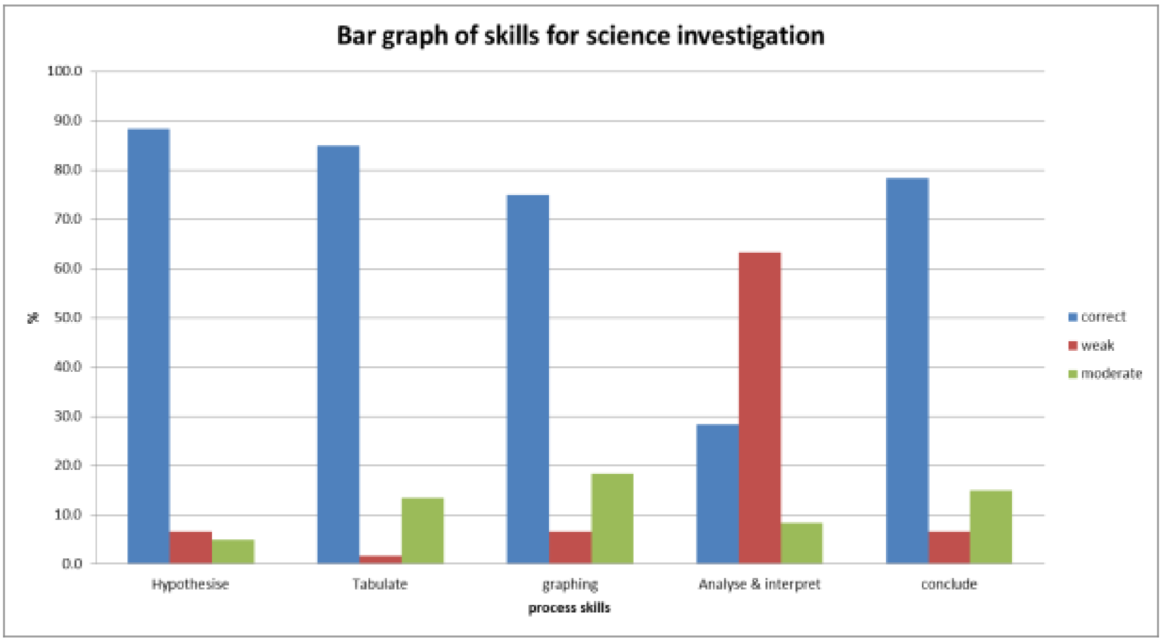
The mean score on the science investigation (M = 65.2) was greater than the mean score on the electricity test (M = 40.9) as shown in table 4.9. This difference was statistically significant, $t\ (59) = 11.1$, $p < 0.05$. It would seem that there is a significant difference between the students' conceptual understanding on the scientific investigation compared with the electricity test. A significant correlation (0.53) exists between the data.

t-Test: Paired Two Sample for Means		
	Electricity project	**Electricity test**
Mean	79.3	40.9
Variance	64.7	313.9
Observations	60	60
Pearson Correlation	0.3563	
Hypothesized Mean Difference	0	
Df	59	
t Stat	17.86	
P(T<=t) two-tail	1.81174E-25	
t Critical two-tail	2.00	

Table 4.10 t-test statistics for project model and test for the 2012 cohort

The mean score on the project model presentation (M = 79.3) was greater than the mean score on the electricity test (M = 40.9) as shown in Table 4.10. This difference was statistically significant, $t(59) = 17.86$, $p < 0.05$. It would seem that there is a significant difference between the students' conceptual understanding on the project model presentation compared with the electricity test. A significant correlation (0.36) exists between the data.

(f) Analysis of science investigation results for the 2012 cohort



	Hypothesise	Tabulate	graphing	Analyse & interpret	conclude
Correct	88.3	85.0	75.0	28.3	78.3
Weak	6.7	1.7	6.7	63.3	6.7
moderate	5.0	13.3	18.3	8.3	15.0

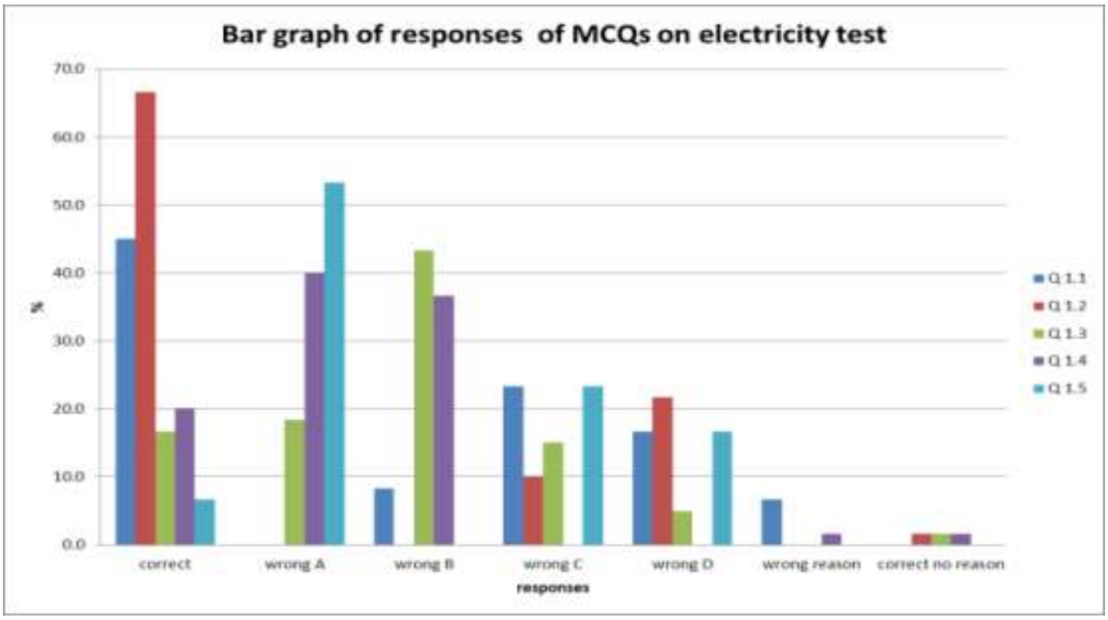
Figure 4.35 Bar graph of process skills on scientific investigation for the 2012 cohort

The 2012 cohort of Natural Sciences students has a well-developed set of process skills as can be inferred from these results in Figure 4.35. This means that they are good at translating between different modes such as from the experimental to the graphical. They also have a weak conceptual understanding of analysing and interpreting data similar to the 2011 cohort. For example, a student wrote: “As can be seen from the graph the lengths of Eureka and Nichrome wire differ”. The graphs give the relationship between potential difference and current and the interpretation should relate to the resistance of the two wires.

(g) Analysis of electricity test results for the 2012 cohort

The test and conceptual trajectory as well as the marking memorandum for each question are presented in Addendum F.

Multiple-choice question with reasons

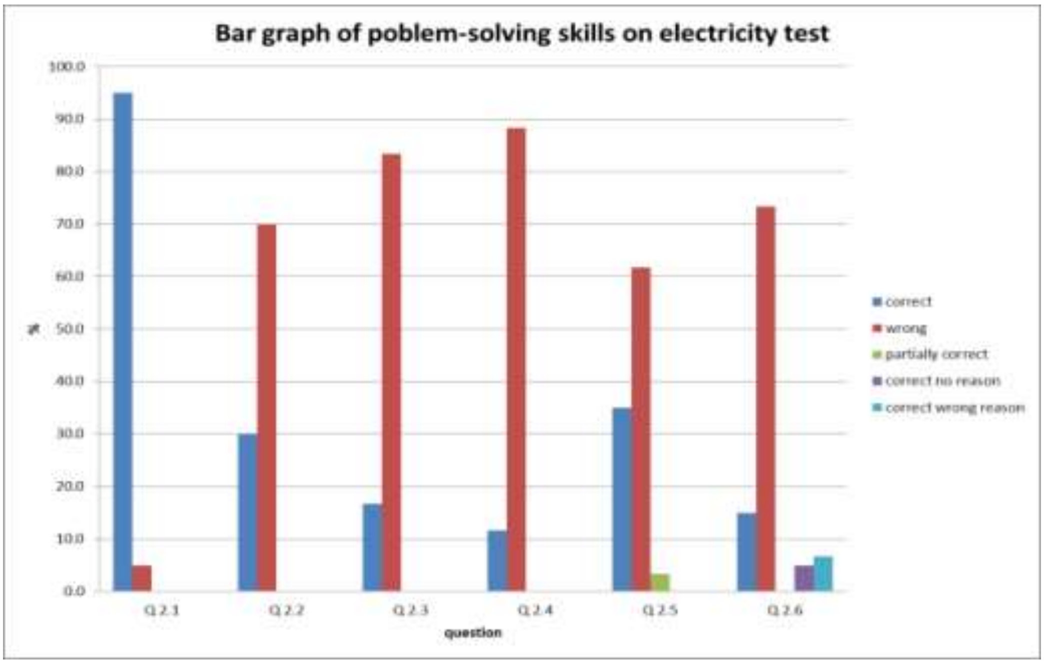


	Q 1.1	Q 1.2	Q 1.3	Q 1.4	Q 1.5
Correct	45.0	66.7	16.7	20.0	6.7
wrong A	0.0	0.0	18.3	40.0	53.3
wrong B	8.3	0.0	43.3	36.7	0.0
wrong C	23.3	10.0	20.0	0.0	23.3
wrong D	16.7	21.7	0.0	0.0	16.7
wrong reason	6.7	0.0	0.0	1.7	0.0
correct no reason	0.0	1.7	1.7	1.7	0.0

Figure 4.36 Bar graph of responses on MCQs on electricity test for the 2012 cohort

It is interesting to note that the same pattern of responses emerged on the multiple-choice questions as was the case for the 2011 cohort. The bar graph in Figure 4.36 illustrates this. Question 1.2 had 66.7% correct responses while question 1.5 had more than 90.0% incorrect responses. The 53.3% of students who chose A as the correct answer seem to have a misunderstanding regarding parallel combinations. The 55.0% of students who chose the wrong answer on question 1.1 appear to not have benefited from the practical exposure to this scenario during class. The 6.7% who gave the right answer appeared to have erroneous reasoning while 23.3% just assume that by removing a light bulb the current would be more. Question 1.4 tested the basics about current and potential difference on a parallel combination. Forty percent (40.0%) of the students missed the fact that the potential difference is the same when they incorrectly responded with A as their answer.

Problem-solving question



	Q 2.1	Q 2.2	Q 2.3	Q 2.4	Q 2.5	Q 2.6
Correct	95.0	30.0	16.7	11.7	35.0	15.0
Wrong	5.0	70.0	83.3	88.3	61.7	73.3
partially correct	0.0	0.0	0.0	0.0	3.3	0.0
correct no reason	0.0	0.0	0.0	0.0	0.0	5.0
correct wrong reason	0.0	0.0	0.0	0.0	0.0	6.7

Figure 4.37 Bar graph of problem-solving skills on electricity test for the 2012 cohort

Figure 4.37 shows that 95.0% of students are able to do straightforward problem-solving as in question 2.1. On question 2.2 they again had a problem (70.0% incorrect) with the split current on a parallel combination. The calculation of the voltages in 2.3 and 2.4 was also very poorly done with more than 80.0% getting it wrong in both cases. The last two questions also required qualitative reasoning and the students again showed that this is an area of poor conceptual understanding on their part. An example of this is shown in Figure 4.38.

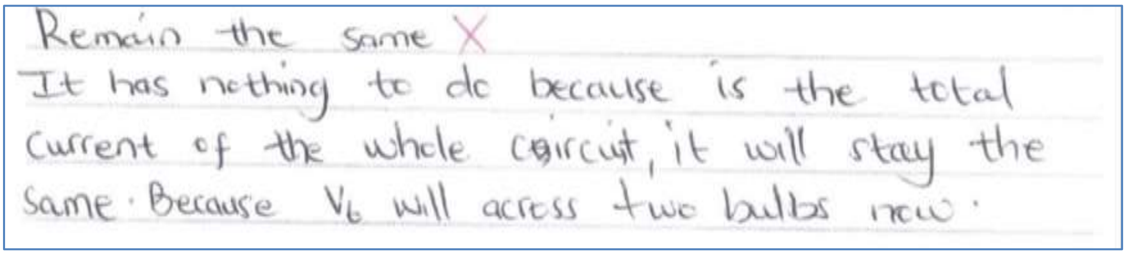
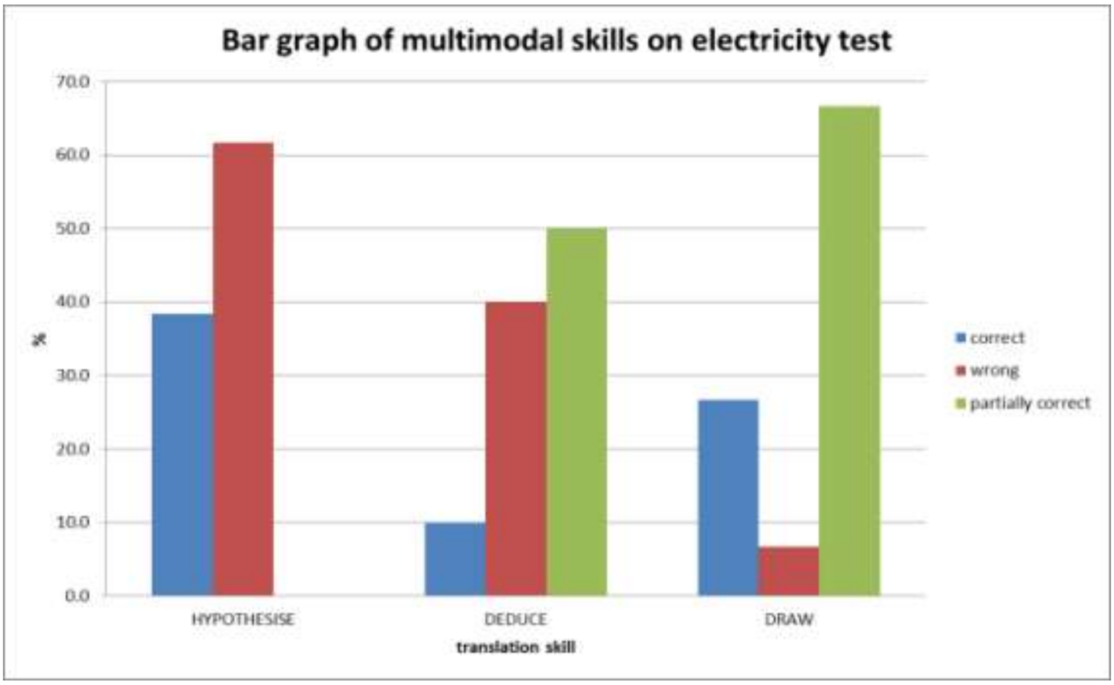

Remain the same X
It has nothing to do because is the total
Current of the whole circuit, it will stay the
same. Because V_6 will across two bulbs now.

Figure 4.38 An example of incorrect qualitative reasoning with the 2012 cohort

Multimodal question



	HYPOTHESISE	DEDUCE	DRAW
correct	38.3	10.0	26.7
wrong	61.7	40.0	6.7
partially correct	0.0	50.0	66.7

Figure 4.39 Bar graph of multimodal translation skills on electricity test for the 2012 cohort

Students' ability to translate from a graphical representation to hypothesise, deduce and draw a circuit diagram points to a poor conceptual grasp in this area as shown in

Figure 4.39. This can possibly be improved upon if the partially correct answers can be addressed. For example, students would state that a directly proportional relationship exists between two variables but they fail to add that the gradient actually says something about the resistance of the conducting wires.

(h) Qualitative analysis of project model presentation for 2012 cohort

Table 4.11 Berland and McNeill's (2010: 772) argumentation product categories for the 2012 cohort

Claim *Answer to a question or problem (design a working project model to apply principles of current electricity)*	Evidence *Scientific data/observations that support the claim (a working model)*	Reasoning *Articulates the logic why the evidence supports the claim*	Appropriateness *Evidence and reasoning are relevant to the problem and scientifically accurate to support claim*	Sufficiency *Quantity and complexity of evidence and reasoning can convince an audience of the claim*
You see there are the lights and the LED is on and the fan.		The resistor was too big so we had to add another wire so that the current can become stronger. And then we also have a graphic explanation of the current.	Appropriate evidence and no reasoning for claim	Insufficient with no justification provided for the claim
We made a wind pump slash energy-- you know those things that turn that generate electricity. This in parallel, the street lights. I also put the light in the motor in a parallel connection.		If one street light goes dead then the others will naturally not go dead. I didn't put a switch on the wind pump, because of the wind it turns when it wants to turn.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
Our circuit is connected in series. If we just put the switch on then the lights will go on and the fan will turn.		We decided not to include the LED in our circuit because it is too big of a resistor.	Appropriate evidence and no reasoning for claim	Insufficient with no justification provided for the claim
This is a house and it only contains a study room. And we have two bulbs here that are connected parallel. We switch off the two bulbs then this one will turn it on like during the day you switch off the two bulbs and then during the night you switch on the lights.		This indicates that if everything is off and the LED will indicate-- like in blackberries like when the blackberry is flat the LED turn red. When the switch is closed then the current flow, then it divides from one of the other bulb to another there.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim

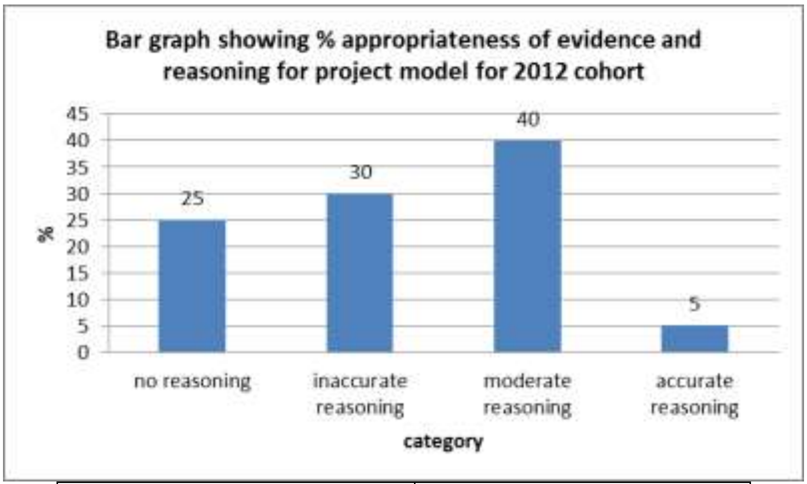
The motor is connected there and it is put in a series circuit. It's the battery, then the two lights, then the switch and then the motor again to the battery.		We had too few wires for that to be possible (if the two lights were connected in parallel).	Appropriate evidence, but inaccurate reasoning.	Insufficient. Low level of complexity to justify claim.
Our circuit is parallel, like over here.		We managed to get everything working and we connected everything from the cell.	Appropriate evidence and no reasoning for claim	Insufficient with no justification provided for the claim
Ok what we have here is a lighthouse with a little light bulb in it. And then we have-- This is rocks and the sea, yeah with the LED in it. Well the two light bulbs are connected in the series.		Because of the high resistance of the LED and the motor we had to connect them in parallel. And because of the design of our project, the one light bulb can be on the other side and then the motor, which is over here, and the LED on this side in parallel.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
We made an airplane runway, as you can see. And then here we have lights where the runway is. And this s a radar. And if you look on this side there is the LED light that is for safety and noticeability for the airplanes. And everything is connected in parallel.		This is a two directional switch. So either the lights shine or if you put it on then the radar moves.	Appropriate evidence, but inaccurate reasoning.	Insufficient. Low level of complexity to justify claim.
It has all the necessary requirements like the motor that turns the propeller and the two lights are here on the front. And the LED light is here at the back. Our circuit is connected in series.		… so you can see the airplane flying at night. So if one of the components stop working then the others will also stop working. If we put the airplane on its back and we turn it on then the propeller can't work and the LED can't work either.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim

We decided to go for a theme that kids could really identify with and that's why we chose Spongebob. And then obviously it would make it interesting for them to learn about electricity. We connected everything in parallel.		...because series didn't work out for us. Then there is a switch on the side that switches him on.	Appropriate evidence, but inaccurate reasoning.	Insufficient. Low level of complexity to justify claim.
We made an airplane. Basically we just used a ruler and that container that your pencil lead comes in and that container that the patch and solution was in. And everything is connected in parallel.		So if that is closed then the circuit is complete and everything works.	Appropriate evidence, but inaccurate reasoning.	Insufficient. Low level of complexity to justify claim.
So this is the stage, there's the lights. What we did was we just took all the components separately. So we took red wire and black wire, positive and negative wire, and connected it all, so it come from the negative one. And this is a rheostat that we put in.		...to make the stage actually go slower. Ok it's supposed to be slower because it's supposed to be a stage that you can dance on that rotates.	Appropriate evidence, but inaccurate reasoning.	Insufficient. Low level of complexity to justify claim.
We decided on a rose and a teddy naturally. OK, we have a parallel circuit.		Ok yes, as I said we used parallel circuit.	Appropriate evidence and no reasoning for claim.	Insufficient with no justification provided for the claim.
This is a Christmas house. As you close the door everything goes on, as my colleague will demonstrate for you. Our connections are in series.		The switch is made out of foil and ah, and putty, so it's quite cheap. So when it comes on it's a bit light, that's why there are holes in it.	Appropriate evidence and no reasoning for claim	Insufficient with no justification provided for the claim

We built an airplane. We used Styrofoam and plastic from hostel and home. And the circuit is connected in series. We used the motor to turn the propeller. The one bulb is here inside so if you turn the switch on then this bulb and the landing bulb here underneath shine.		...so if one light blows or the motor blows then it won't work.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
We made a ferris wheel. And then we used the motor to turn the ferris wheel. We connected it in parallel.		...so if one of our spotlights don't work then the people can still ride the ferris wheel. It's not too fast so the people aren't going to fall off.	Appropriate evidence, but inaccurate reasoning.	Insufficient. Low level of complexity to justify claim.
We decided to build a light house. We connected the current in parallel. We inserted a variable resistor. When I put it on the light goes on and if you rest here on the variable resistor then the motor will work.		We first had it in series but it didn't work because the resistance was too much. We also took the LED out because it took too much resistance. ...so we can regulate the speed of that movement.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
A water turbine is a rotary engine that takes energy from moving water. You may have noticed that it contains two light bulbs and an LED light. It is connected in parallel.		It is the source that provides energy for the flow of current. It is connected in parallel because the current is spread evenly. Thus, the light bulbs will glow with the same brightness. We chose to connect it in parallel and not in series because if connected in series it would have pulled too much current and the bulbs would have glowed very dimly. And if the one bulb obviously is disconnected then the other one will still be glowing.	Appropriate evidence to support the claim. Accurate reasoning for claim.	Sufficient and good degree of complexity

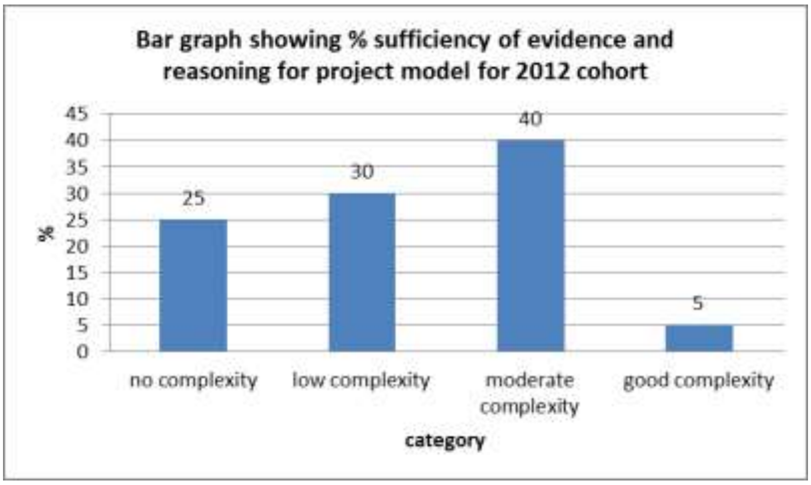
We made a water mill. There are two lights and two batteries. Our circuit is in parallel.		If the one light dies then the other light, the other light won't go dead and the motor will still work.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
We created a space bug. It has two motors. It's connected in series and in parallel. The LED's is connected in series. The feelers on top are connected to the switch.		...series because it is connected directly to the battery and then we have another circuit where the motors are connected in parallel. So if it hits a wall at a certain angle it puts the one switch off and then it can turn the other motor.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim

Students were able to present working models of basic electric circuits as illustrated in Table 4.11. This constituted the evidence of their claim in the argumentation framework. The appropriateness (i.e. relevance and scientific accuracy) and sufficiency (i.e. quantity and complexity) of the evidence and reasoning were found lacking. It was found that only 40.0% and 5.0% of students used moderate to accurate reasoning respectively when explaining their model. This implies that a large proportion demonstrated poor argumentation skills by failing to substantiate their claims adequately. Likewise, the complexity of their arguments was also weak. The quantification of the qualitative data is presented in Figures 4.40 and 4.41 below.



	% of projects
no reasoning	25.0
inaccurate reasoning	30.0
moderate reasoning	40.0
accurate reasoning	5.0

Figure 4.40 Bar graph of % appropriateness of evidence and reasoning for the 2012 cohort



	% of projects
no complexity	25.0
low complexity	30.0
moderate complexity	40.0
good complexity	5.0

Figure 4.41 Bar graph of % sufficiency of evidence and reasoning for the 2012 cohort

(j) Overall reflection after cycle 2 of the teaching experiment

The 2012 cohort of students attained better results on average than the 2011 cohort of students on the three assessments. This particular cohort benefited from extensive consultation during and after laboratory sessions. This is not something that was planned but evolved simply because the students were keen to go beyond simple manipulation of apparatus. They asked more questions relating to the investigations and what was required to manipulate the data without getting the actual answers. For example, they were reminded that emphasis was placed on the dependent, independent and controlled variables. It was a matter of applying that knowledge to the tabulation and graphing of the data. It would seem that their process skills in this regard were well developed, although analysis and interpretation is still an area of concern.

Although the students are afforded opportunities to work collaboratively and discuss whatever they are engaged with in direct current electricity, their argumentation skills are still lacking. The justifications for the claims that they make, particularly in relation to why their models work, are still inappropriate or absent. This is also evident in the formal written test where their problem solving ability is deficient from a quantitative as well as qualitative perspective. Questions that require justification or substantiation of their answers are poorly done. A lot of classroom time is spent doing problem - solving using similar questions that the students encounter in their assessment. What has emerged is that although the classroom dynamics for inquiry-based teaching and learning places an emphasis on engagement and dialogue, there are instances where a focus on traditional explanation of concepts is necessary. This implies that the teacher educator has to integrate direct instruction methods, particularly as far as problem-solving is concerned.

The time that students spent presenting their project model cut into the time for practical investigations such as the magnetic effect of an electric current. The benefits derived from engaging in designing and developing their model are greater than completing this investigation. In the next cycle of the teaching experiment I want to look at the questions that are included in the assessment test and what might give rise to misinterpretation or misunderstanding. This has to be done without compromising on the level of cognitive demand.

4.3.3.3 Cycle 3 – refinement with 2013 cohort

(a) Participants

The participants are 47 second-year level Natural Sciences students (6 males and 41 females) enrolled in a Bachelor of Education (B. Ed) programme at university.

(b) Data collection

The data collection also took place over a period of 6 weeks during the presentation of the unit of current electricity. During the second week students do the scientific investigation of the factors that influence the resistance of a conductor. The session allows them 90 minutes to complete their data collection. They submit a scientific report a week later which is assessed according to a rubric with a focus on process skills such as hypothesising, graphing, analysis and interpretation, etc. The marks and each process skills category is captured in Microsoft Excel® for all 63 students.

During the final week they present their project model in groups of three. This is captured on video and assessed with a rubric which looks at the functioning of the model, creativity and the students' explanation. The marks are captured in Excel and all the presentations are transcribed for later analysis of the students' argumentation product. The final assessment test on electricity follows after the 6 weeks. The questions include multiple-choice questions, problem-solving as well as multimodal translation type questions. The tests are assessed according to a marking memorandum and the marks are captured in Excel and the students' responses on each question are categorised as well for data analysis.

(c) Data analysis

Descriptive statistics is used to present the data in a summarised form and also show the distribution of the data. Inferential statistics is used to make comparisons between groups and the t-test is used to discover any statistically significant differences between the means of two sets of scores for the same group of students.

The qualitative data for the research study was obtained from the transcriptions of the video recordings of the project presentation. The data was transferred into Excel according to Berland and McNeill's (2010: 772) argumentation product categories outlined in chapter 3. Data reduction occurs as part of the data is selected for coding. Content analysis is undertaken and the process of enumeration can then take place whereby the frequencies of codes are counted. Triangulation of both quantitative and qualitative data is then done.

(d) Quantitative analysis of data of three assessment tasks

A detailed table of the results obtained in each assessment task, viz. scientific investigation, project model presentation and electricity test is presented in Addendum G. A bar graph of the average percentage obtained in the three assessments is shown in Figure 4.42. The students did well on all the assessment activities, but a closer look at the descriptive statistics (Table 4.12) gives a better feel for the distribution of the data. The median for the test is 78.0 which implies that 50% of the students obtained a mark higher than this. The median for both the science investigation and project presentation is higher than the mean. In order to answer the research questions, a more detailed analysis of the questions on the test follows later.

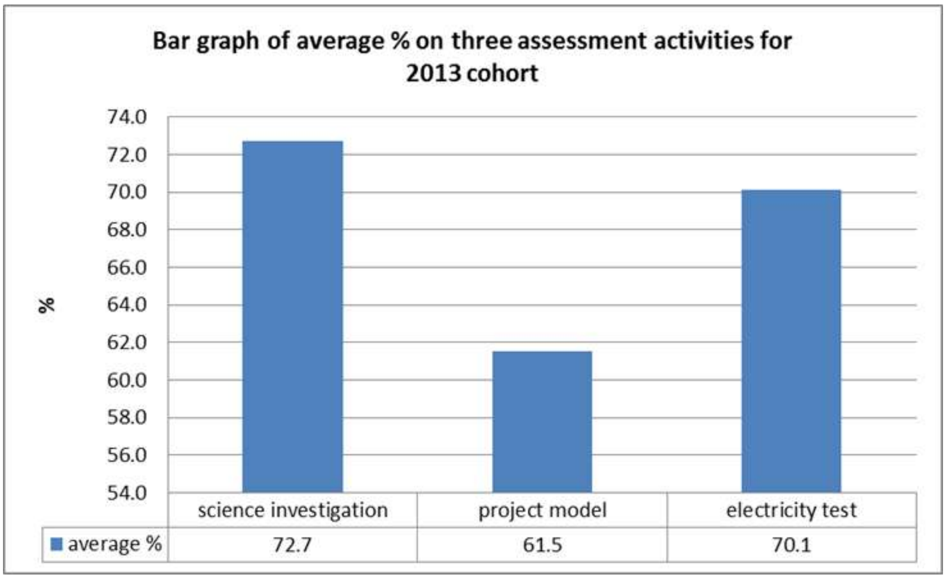


Figure 4.42 A bar graph of the average % on the three assessment tasks for the 2013 cohort

(e) Descriptive statistics for the 2013 cohort

science investigation		group project		test	
Mean	72.7	Mean	61.5	Mean	70.1
Standard Error	3.8	Standard Error	3.5	Standard Error	3.6
Median	80.0	Median	67.5	Median	78.0
Mode	92.5	Mode	75.0	Mode	88.0
Standard Deviation	26.1	Standard Deviation	24.1	Standard Deviation	24.5
Sample Variance	681.2	Sample Variance	583.0	Sample Variance	599.2
Kurtosis	2.2	Kurtosis	3.1	Kurtosis	2.4
Skewness	-1.7	Skewness	-2.2	Skewness	-1.6
Range	100	Range	80	Range	100
Minimum	0	Minimum	0	Minimum	0
Maximum	100	Maximum	80	Maximum	100
Sum	3417.5	Sum	2892.5	Sum	3295
Count	47	Count	47	Count	47

Table 4.12 Descriptive statistics of 3 assessments for the 2013 cohort

(f) Analysis of t-test results for the 2013 cohort

t-Test: Paired Two Sample for Means		
	science investigation	**Electricity project**
Mean	72.7	61.5
Variance	681.2	583.0
Observations	47	47
Pearson Correlation	0.4389	
Hypothesized Mean Difference	0	
Df	46	
t Stat	2.87	
P(T<=t) two-tail	0.0062	
t Critical two-tail	2.01	

Table 4.13 t-test statistics for science investigation and project model for the 2013 cohort

The mean score on the science investigation (M = 72.7) was higher than the mean score on the project model presentation (M = 61.5) as shown in Table 4.13. This difference was statistically significant, t (46) = 2.87, $p < 0.05$. It would seem that there is a significant difference between the students' conceptual understanding on the science investigation compared with the project model presentation. There also appears to be a significant relationship between the scores as the correlation of 0.44 indicates.

t-Test: Paired Two Sample for Means		
	science investigation	**Electricity test**
Mean	72.7	70.1
Variance	681.2	599.2
Observations	47	47
Pearson Correlation	0.3826	
Hypothesized Mean Difference	0	
Df	46	
t Stat	0.64	
P(T<=t) two-tail	0.5285	
t Critical two-tail	2.01	

Table 4.14 t-test statistics for science investigation and test for the 2013 cohort

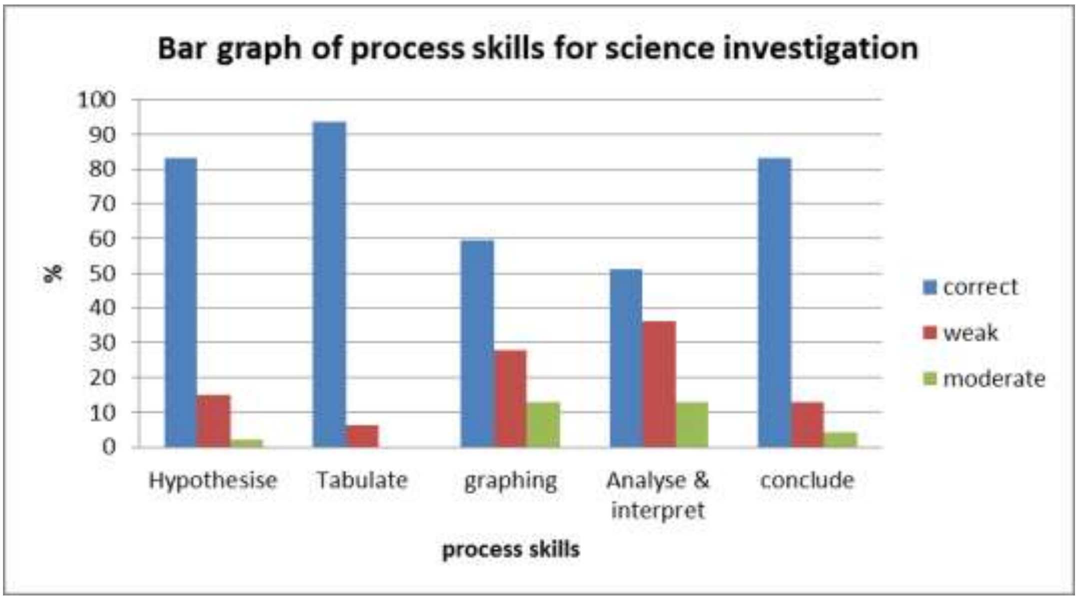
The mean score on the science investigation (M = 72.7) was higher than the mean score on the electricity test (M = 70.1) as shown in Table 4.14. This difference was not statistically significant, t (46) = 0.64, $p > 0.05$. It would seem that there is no significant difference between the students' conceptual understanding on the scientific investigation compared with the electricity test. There is also a significant correlation (0.38) between the data.

t-Test: Paired Two Sample for Means		
	Electricity project	**Electricity test**
Mean	61.5	70.1
Variance	583.0	599.2
Observations	47	47
Pearson Correlation	0.6844	
Hypothesized Mean Difference	0	
Df	46	
t Stat	-3.04	
P(T<=t) one-tail	0.0019	
t Critical two-tail	2.01	

Table 4.15 t-test statistics for project model and test for the 2013 cohort

The mean score on the project model presentation (M = 61.5) was less than the mean score on the electricity test (M = 70.1) as shown in table 4.15. This difference was statistically significant, $t(46) = -3.04$, $p < 0.05$. It would seem that there is a significant difference between the students' conceptual understanding on the project model presentation compared with the electricity test. A significant correlation (0.68) exists between the data.

(g) Analysis of science investigation results for the 2013 cohort



	Hypothesise	Tabulate	graphing	Analyse & interpret	conclude
correct	83	93.6	59.5	51	83
weak	14.9	6.4	27.7	36.2	12.8
moderate	2.1	0.0	12.8	12.8	4.2

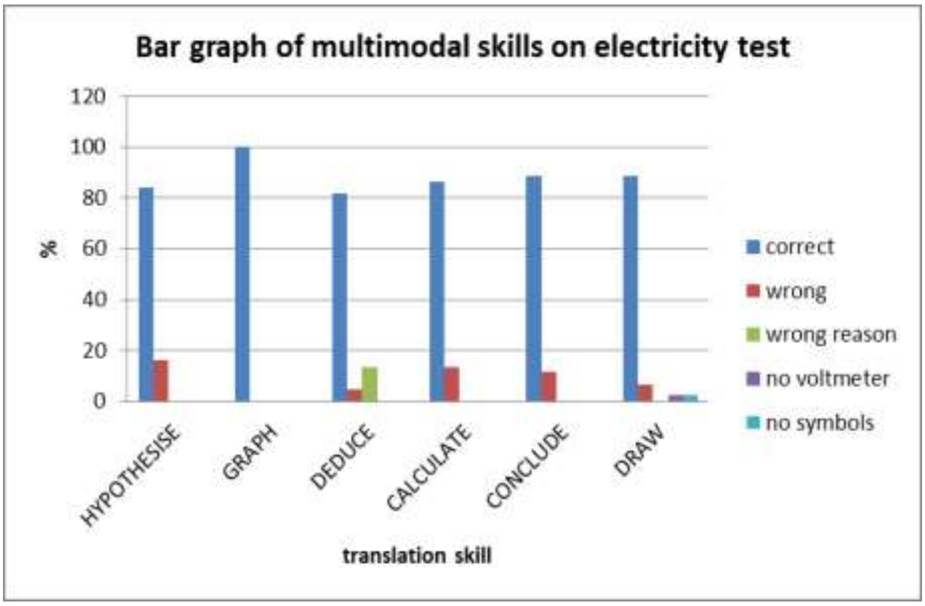
Figure 4.43 Bar graph of process skills on scientific investigation for the 2013 cohort

Figure 4.43 shows that the overall process skills for this group is well-developed which means that they are able to translate from one mode to the other. However, translating the data into a graph is an area of concern when some elementary things such as labelling the axes are not done. Although their ability to analyse and interpret is above 50.0% on average, this is obviously an area that can be improved upon.

(h) Analysis of electricity test results for the 2013 cohort

The test and conceptual trajectory as well as the marking memorandum for each question are presented in Addendum H.

Multimodal question

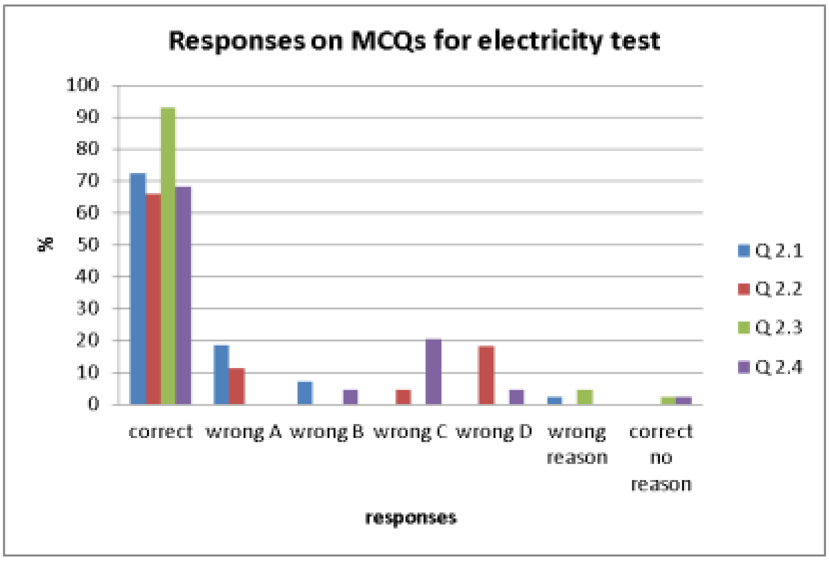


	HYPOTHESISE	GRAPH	DEDUCE	CALCULATE	CONCLUDE	DRAW
correct	84	100	81.8	86.4	88.6	88.6
wrong	16	0.0	4.6	13.6	11.4	6.8
wrong reason	0.0	0.0	13.6	0.0	0.0	0.0
no voltmeter	0.0	0.0	0.0	0.0	0.0	2.3
no symbols	0.0	0.0	0.0	0.0	0.0	2.3

Figure 4.44 Bar graph of multimodal translation skills on electricity test for the 2013 cohort

The results of the 2013 cohort's ability to translate from one mode to the other indicate a good conceptual understanding of direct current electricity. It would appear that their exposure to these skills in class has paid dividends in the test. Figure 4.44 clearly shows that the students are able to translate data from a table into a graph, formulate a hypothesis and make valid deductions. They are also able to calculate the resistance from the data, draw acceptable conclusions and construct a diagram of the experimental set-up.

Multiple-choice question with reasons



	Q 2.1	Q 2.2	Q 2.3	Q 2.4
Correct	72.3	65.9	93.2	68.3
wrong A	18.4	11.4	0.0	0.0
wrong B	7	0.0	0.0	4.5
wrong C	0.0	4.5	0.0	20.4
wrong D	0.0	18.2	0.0	4.5
wrong reason	2.3	0.0	4.5	0.0
correct no reason	0.0	0.0	2.3	2.3

Figure 4.45 Bar graph of responses on MCQs on electricity test for the 2013 cohort

A new set of multiple-choice questions was developed to test the basics of series and parallel circuits. Figure 4.45 shows that the students have a good overall understanding, but the wrong responses also point to a weak understanding on the part of some. These relate to effective resistance, inverse proportionality of current and resistance, and the potential difference in a parallel combination. Figure 4.46 below illustrates a typical incorrect answer such as stating that if the resistance is less, then the current is also lower.

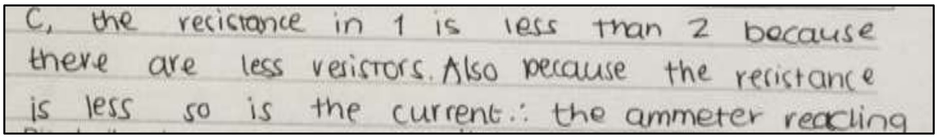
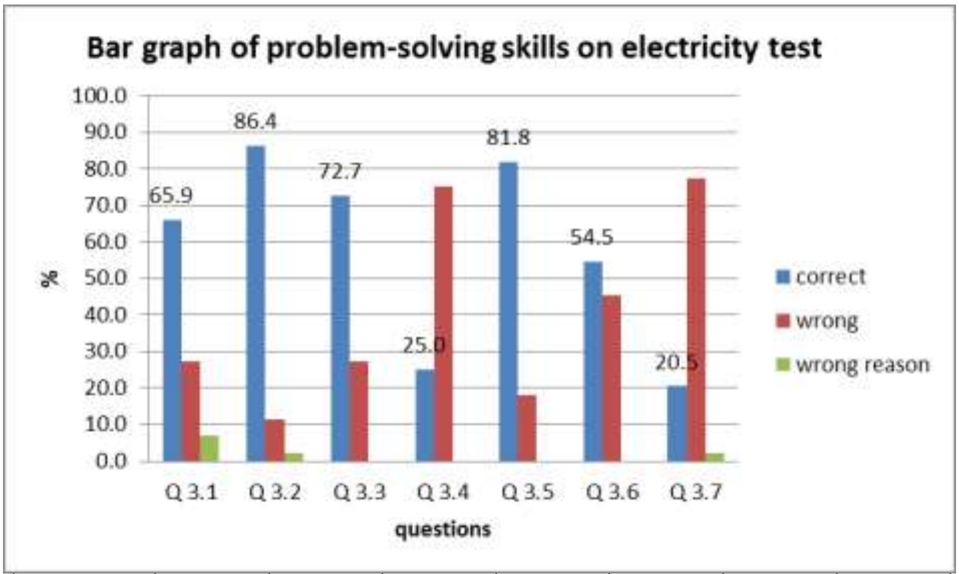

C, the recistance in 1 is less than 2 because
there are less verictors. Also pecause the recistance
is less so is the current.∴ the ammeter reading

Figure 4.46 Incorrect answer on a MCQ question for the 2013 cohort

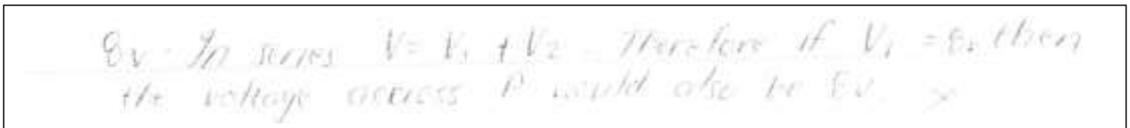
Problem-solving



	Q 3.1	Q 3.2	Q 3.3	Q 3.4	Q 3.5	Q 3.6	Q 3.7
Correct	65.9	86.4	72.7	25.0	81.8	54.5	20.5
Wrong	27.3	11.4	27.3	75.0	18.2	45.5	77.3
wrong reason	6.8	2.3	0.0	0.0	0.0	0.0	2.3

Figure 4.47 Bar graph of problem-solving skills on electricity test for the 2013 cohort

The 2013 cohort of students have good problem-solving skills and a good conceptual grasp of electricity as shown in Figure 4.47. The one area of weakness is the calculation of potential difference as well as a qualitative understanding thereof. This is illustrated by a student's answer in Figure 4.48.



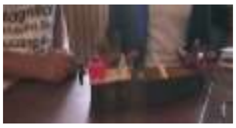
8V. In series $V = V_1 + V_2$. Therefore if V_1 = 8V then the voltage across P would also be 8V.

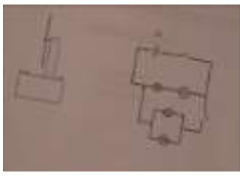
Figure 4.48 A student's answer to a potential difference question for the 2013 cohort

(i) Qualitative analysis of project model presentation for 2013 cohort

Table 4.16 Berland and McNeill's (2010: 772) argumentation product categories for the 2013 cohort

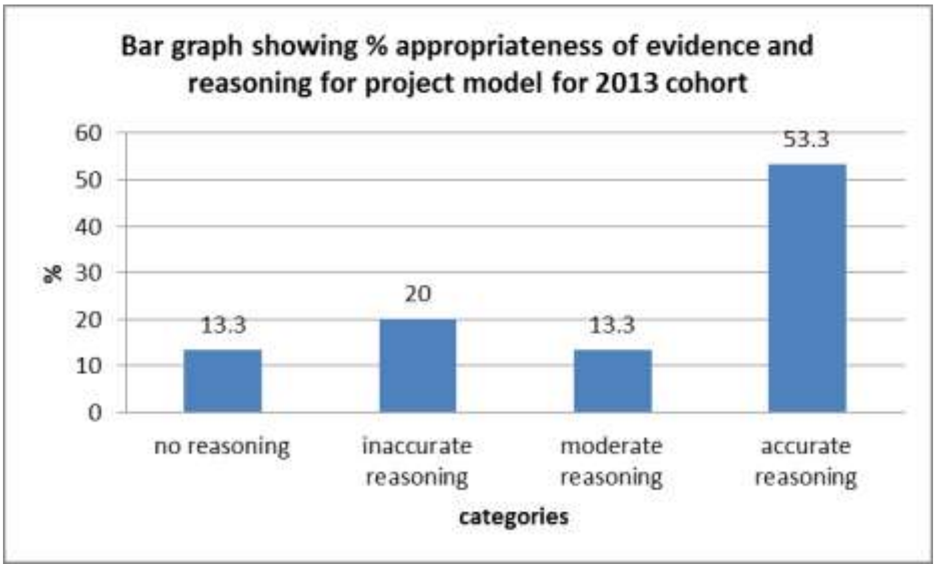
Claim	Evidence	Reasoning	Appropriateness	Sufficiency
Answer to a question or problem (design a working project model to apply principles of current electricity)	***Scientific data/observations that support the claim (a working model)***	***Articulates the logic why the evidence supports the claim***	***Evidence and reasoning are relevant to the problem and scientifically accurate to support claim***	***Quantity and complexity of evidence and reasoning can convince an audience of the claim***
We have a parallel circuit here with the light bulb and the motor is in series		We wanted to make one circuit with the motor and light bulb in, but we struggled to make the motor go in one circuit.	Appropriate evidence, but inaccurate reasoning.	Insufficient. Low level of complexity to justify claim.
We created a circuit that shows the principles of electricity and how we understand and interpret it		In our circuit the two cells are the source of electrical energy. The second component is the conducting wires which consist of copper wire and insulation around it. The next component is the switch that works the same as the one at home. It allows current to flow or prevents it from flowing. The last components are the light bulbs and the motor. The purpose of these is to offer resistance to the current.	Appropriate evidence and accurate reasoning to support claim	Sufficient with high degree of complexity, but well-reasoned for audience to follow
We made something that interests all of us so we thought about the movies and the mirrors with the lights around it.		We tried to put everything in one circuit with two batteries but it did not work. So we took two circuits, one for the fan and one for the light. The fan is in series and the lights in parallel. If we unscrew the one then the rest work.	Appropriate evidence with moderate reasoning to justify claim	Insufficient. Moderate level of complexity
What we have is the switch is connected in series to the batteries and inside we have the motor and the light bulb connected in parallel.		We have an opening over here to see how it is connected. Not much else to say. It was difficult to get it to function.	Appropriate evidence, no reasoning to justify claim	Insufficient and no justification to support claim.

We need a source of energy, conducting wires, a motor and two light bulbs. The current is connected in parallel. The main current is divided so that the sum of the currents is equal to the main current.		The potential difference is the same everywhere in parallel and the bulbs are equally bright. Say one of the light bulbs is broken then the fan still turns. The circuit is now in series and the light bulb is brighter and the fan turns faster. The current in series is the same and the potential difference is divided. If we reconnect then everything is again in parallel.	Appropriate evidence and accurate reasoning for claim	Sufficient with good degree of complexity
In order for a circuit to work correctly and for current to flow we need a source of energy, conducting wires and components that convert the electrical energy to light. The motor turns like this. The current flows from positive to negative – we talk about a conventional current.		We can observe that both the bulbs will shine equally – have equal brightness. If we had an ammeter reading it will be the same everywhere in the circuit. In the series circuit if there is a break in connection - a bulb blows or something there is an interrupted flow of energy. None of the other things will work. If we were to add another bulb or motor there will be an increase in the total resistance which means the total current would decrease – that is an indirectly proportional relationship.	Appropriate evidence and accurate reasoning for claim	Sufficient with good degree of complexity
We decided to build a boat. The basic circuit as you can see consists of two light bulbs, two batteries and a motor and a switch. The light bulbs are in parallel and the batteries are the source that supplies energy.		The energy moves from the battery that supplies the energy to the motor – the lights bulbs burn and the motor can turn. It flows from positive to the negative pole. We used these batteries because the smaller ones are too weak to let the bulbs and motor work at the same time. The batteries potential difference is 3 volts which is still not very strong. Our bulbs are in parallel so when we unscrew the one the other still works. You can see the current divides in parallel.	Appropriate evidence to support the claim. Accurate reasoning for claim.	Sufficient with good degree of complexity

We made something very simple that illustrates the basic concepts of electricity. Firstly our cells are in series and then we have a little motor.		When all the wires are connected correctly then only the two with the correct answer will indicate to us that there is a current. For example cells in series have positive to negative pole – the colour wheel turns – also the light does not burn because the motor takes all the current. In parallel cells are connected positive to positive. You see the wheel does not turn if the answer is wrong. We also saw that when the current goes through the light is supposed to burn – the motor takes the most power so that the bulb is dimmer.	Appropriate evidence to support the claim. Accurate reasoning for claim.	Sufficient and good degree of complexity
We used the alarm clock because the battery holder did not work. We connected the batteries and switch in series and the globes and the motor in parallel		When we connected them in series the bulbs did not light.	Appropriate evidence and no reasoning for claim	Insufficient and no justification to support claim.
Our project is a wind turbine – we used recycled materials. The current is connected in parallel as you can see. We put in two switches. The second switch puts on the lights but the fan turns slower	 	The current divides at the first switch then it goes through the motor and the two light bulbs. Because it is connected in parallel the current strength is divided but the potential difference is the same.	Appropriate evidence and accurate reasoning for claim	Sufficient with good level of complexity to justify claim
What we built is a stage – this is our people performing. When you put on the switch our globes are connected in parallel.		If you remove one of these or they fuse or something this is still working. That's why we chose a parallel connection because it is advantageous. The battery is in series with the switch and this light bulb here.	appropriate evidence and accurate reasoning for claim	sufficient with good level of complexity to justify claim

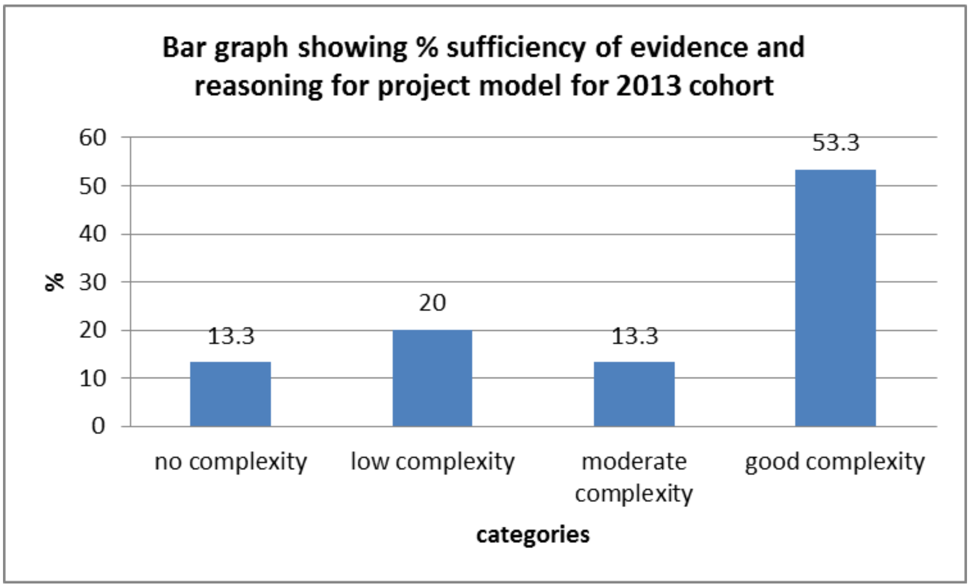
We have something like in a baby's room it shines and makes figures. We used two light bulbs, a switch and a source of energy. We made a fan for extra.		We connected it is series – the mother does not have to go from one end to the other. There the bulbs are working.	Appropriate evidence, but inaccurate reasoning to justify the claim.	Insufficient. Low level of complexity to justify claim.
We connected our circuit in series and our motor in parallel. We can also convert energy like mechanical to electrical – this is like a windmill.		…parallel because it uses a lot of current. The reason we connected our circuit in series is because each component is important. When we disconnect one bulb everything goes out.	Appropriate evidence, but inaccurate reasoning to justify claim	Insufficient. Low level of complexity to justify claim.
This represents a fake disaster. The battery is the tsunami. If the switch is turned on then it turns.		We have a parallel circuit – LED, light and motor divided the volts equally. If the LED is in series then it takes all the volts.	Appropriate evidence with moderate reasoning to justify claim	Sufficient with moderate level of complexity to justify claim
We need conducting wires and a source of energy – we include a light bulb and a fan which are in parallel. Everything else is in series. We built a lighthouse – the light is series with the battery and the fan in parallel.	 	If the switch is open the bulb will not light or the fan won't turn. When the switch is closed then the two work because we have a complete circuit. We first tried another way to see if it will work. But it did not work so here we see the fan as well as motor works.	Appropriate evidence with accurate reasoning to justify claim.	Sufficient and good degree of complexity

Students were able to present working models of electric circuits which constituted the evidence of their claim in the argumentation framework as shown in Table 4.16. The appropriateness (i.e. relevance and scientific accuracy) and sufficiency (i.e. quantity and complexity) of the evidence and reasoning were found lacking in some respects. It was found that 13.3% and 53.3% of students used moderate to accurate reasoning respectively when explaining their model. This implies that a large proportion demonstrated poor argumentation skills by failing to substantiate their claims adequately. Likewise, the complexity of their arguments was also weak. The quantification of the qualitative data is presented in Figures 4.49 and 4.50 below.



	% of projects
no reasoning	13.3
inaccurate reasoning	20
moderate reasoning	13.3
accurate reasoning	53.3

Figure 4.49 Bar graph of % appropriateness of evidence and reasoning for the 2013 cohort



	% of projects
no complexity	13.3
low complexity	20
moderate complexity	13.3
good complexity	53.3

Figure 4.50 Bar graph of % sufficiency of evidence and reasoning for the 2013 cohort

(j) Overall reflection after cycle 3 of the teaching experiment

The 2013 cohort of students attained good results in their assessments which could be interpreted as them having a good conceptual understanding of direct current electricity. This is manifested in the quantitative and qualitative analysis of the data from the teaching and learning activities that the students were engaged in.

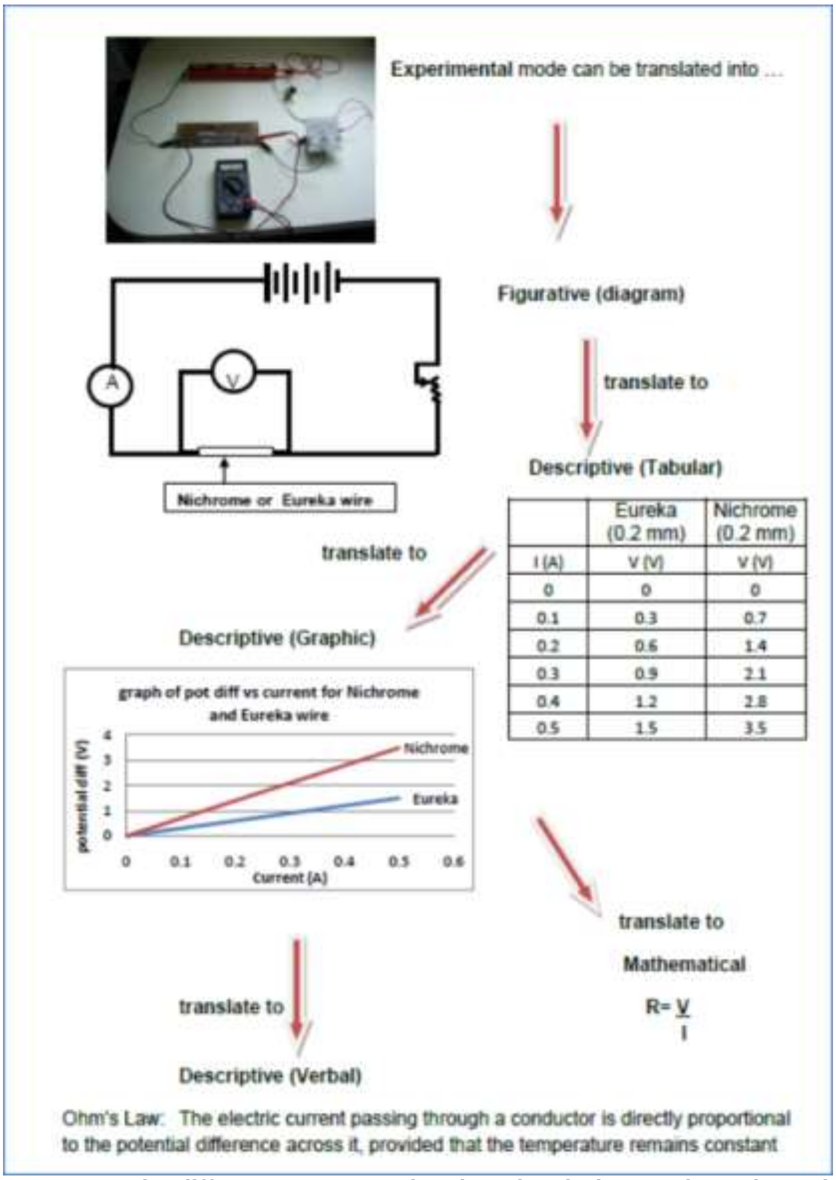
Their process skills are well-developed as exhibited in their scientific investigation report. It would seem that analysis and interpretation of results is a common problem with all three cohorts in this study. The students' ability to translate data into various representations is also evident in their answers on the formal test with few areas of weakness that are apparent.

A new set of multiple-choice questions were developed that also required justification of a correct answer. These questions still tested the students' understanding of direct current electricity with an emphasis on the concepts that had been dealt with in class. The students did very well on these questions which showed that the focus on inquiry was bearing fruit. Their understanding was also amply demonstrated in the problem-solving questions. This could possibly be ascribed to the renewed focus on solving problems in class that clearly demonstrated concepts such as splitting of current in parallel as well as more qualitative reasoning type questions. As with the 2012 cohort of students, this clearly demonstrates that a narrow focus on inquiry-based teaching strategies does not in itself foster the development of students' conceptual understanding of direct current electricity. There is a need to incorporate traditional pedagogical strategies.

The students also did reasonably well in presenting their project models. More importantly, their argumentation skills were better developed than the other two cohorts. Whilst all of them got the same opportunities to work collaboratively and engage in discussion, it would seem that the 2013 cohort made better use of the inquiry-based sessions to develop their understanding.

4.3.4 PHASE 4: Reflection of design principles

Design-based research is underpinned by a pragmatic philosophical standpoint in which qualitative as well as quantitative data are collected and analysed. In this research study the pre-service science teacher's conceptual understanding of direct current electricity has been developed through various pedagogical strategies. These include an exposure to scientific investigations in the laboratory to develop not only process skills, but the ability to translate between different modes. Figure 4.51 below shows diagrammatically how this can be done.



	Eureka (0.2 mm)	Nichrome (0.2 mm)
I (A)	V (V)	V (V)
0	0	0
0.1	0.3	0.7
0.2	0.6	1.4
0.3	0.9	2.1
0.4	1.2	2.8
0.5	1.5	3.5

Figure 4.51 The different representational modes during a science investigation

These opportunities are also used for the students to work collaboratively to develop their conceptual understanding through dialogic interaction. The laboratory sessions are also designed to give them hands-on opportunities to work with electricity kits. The students also build their own models which must be explained using qualitative reasoning and therefore demonstrate their argumentation skills. The students build a 3-D model that exhibits the principles of basic current electricity that they learnt in class over a six week period. They work in groups of up to three and must demonstrate that the model works and explain the principles of direct current electricity involved.

The core design principle adopted in this study is to design a domain-specific learning environment that advocated inquiry-based science to develop PSSTs conceptual understanding of direct current electricity. When exposed to hands-on investigations about series and parallel combinations of light bulbs, the qualitative understanding acquired during this particular representational mode can be translated into the written mode such as a worksheet. Students are also able to interpret formal representations such as graphs and translate to a written or visual mode such as a diagram to develop their conceptual understanding. Repeated exposure to the different modalities can help in constructing appropriate meanings.

Fisher's exact test was used to analyse categorical data of the process skills of students during the science investigations. The purpose was to determine whether the data provide sufficient evidence that the proportions of students having appropriate science process skills differ for the three cohorts of students since they are independent samples. The data in Addendum I show that except for the process skill of hypothesising, all the other skills differ in terms of the extent to which it is appropriately developed.

It is important that students' problem-solving ability be developed through carefully selected problems which address the various concepts such as current, potential difference and resistance. These should start at the basic level and lead to more challenging application type problems. Their understanding can also be tested at the end of the unit by focusing on types of questions which have been dealt with in class and which span all the cognitive levels. This particular aspect of the study shows that traditional direct methods of instruction cannot be discarded because there are certain concepts that students continue to struggle with which require detailed explanation by the educator. This is elaborated on in the retrospective analysis (Chapter 5).

In this chapter I have outlined the preliminary phase of the design process and the different phases during the formal enactment of the teaching experiment over three cycles with three cohorts of PSSTs. In the next chapter a retrospective analysis is done by evaluating the data in more detail, and which places the findings within a theoretical framework.

CHAPTER 5

RETROSPECTIVE ANALYSIS

The retrospective analysis "results in situated accounts of learning that relate learning to the means by which it can be supported and organized (Cobb, et al., 2003: 13). It is aimed at providing a rigorous analysis of the data which serves as a means to make recommendations with regard to the teaching experiment (Bradley, 2013: 10). The inquiry-based social constructivist learning environment was designed to encourage student participation in all the activities relating to the development of their conceptual understanding of direct current electricity. The retrospective analysis delves deeper into the design heuristics that emanated from the transformative conjecture-driven teaching experiment. It is important to note that the content and pedagogy comprise the two components of this teaching experiment. Thus, the focus of the retrospective analysis is on the pedagogical approaches that best promote the PSSTs learning and understanding of the content of direct current electricity. As Molina, Castro and Castro (2007: 437) argued, it leads to "a coherent history of the evolution of the researchers´ conjectures and the evolution of the students´ behaviour, thinking and performance throughout the in-class interventions".

I would like to reiterate the features of the domain-specific learning environment that address the conjecture that advocates inquiry-based science rather than a didactic expository approach in the teaching, learning and assessment of direct current electricity with PSSTs. These can be summarised as:

(a) Tasks and activities were embedded within an inquiry framework that provided ‘’hands-on” and ‘’minds-on” opportunities for the students to engage in deeper learning as opposed to being docile recipients of information from the teacher educator.

(b) Collaboration during investigations encouraged discussion to help develop explanatory models and justification for any observed phenomena or claims that the students make.

(c) Tasks and activities were designed to help develop the students’ basic as well as integrative process skills in a manner that enhanced their multimodal translation skills.

(d) Problem-solving skills were developed by engaging in structured problem sets which include quantitative and qualitative questions that are progressively more cognitively demanding, and thus extends into the students’ ZPD.

(e) The assessment opportunities were linked to the inquiry-based classroom activities and were designed to elicit the students’ conceptual understanding of direct current electricity, both quantitatively and qualitatively.

I will now retrospectively look at the teaching experiment and elaborate on the evidence of the data, and place it within a theoretical context.

5.1 Connecting teaching starting points with endpoints

(a) The introduction to current electricity with PSSTs starts with a common inquiry-based activity that is used to elicit the students’ understanding of a complete circuit as outlined by McDermott,Shaffer and Constantinou (2000:

414) in their research. The activity involves the connecting of a light bulb to a battery using a single wire to make the bulb glow. This practical hands-on activity is for many of the students a rare opportunity to engage in an investigation in the laboratory. This is evident from the tentativeness which many of them display when handling basic equipment such as a light bulb and battery. Many of the students across the cohorts needed assistance with this activity. The models which the students displayed also correspond in many instances to those found in the literature such as the unipolar, clashing currents, attenuation and sharing models (Shipstone, 1985; Afra, et al., 2009). The more important outcome of this exercise is that the students must reason qualitatively and build on their understanding as they encounter more complex electric circuits. For many of the students this understanding was demonstrated when they explained their project model towards the end of the module. Below follow some quotes taken directly from the transcripts for the three cohorts as presented in chapter four:

Student 1: *"You need a closed circuit and an energy source for energy to flow. This circuit is a closed circuit when the switch is on the right and it is off when the switch is on the left. We decided to connect the light bulbs in parallel. … The reason for this is that the one light bulb will continue to shine if the other one is screwed out and it will also shine brighter".*

Student 2: *"The potential difference is the same everywhere in parallel and the bulbs are equally bright. Say one of the light bulbs is broken then the fan still turns. The circuit is now in series and the light bulb is brighter and the fan turns faster".*

The above all illustrate how these students conceptualised a closed circuit and use the evidence and their scientific knowledge for their explanation (Carrin, Bass & Constant, 2005). It is pertinent to note that this is not an attempt to make a generalisation about the participants in this study, but to cite instances of where the students developed an understanding based on the activities that they were engaged in. As noted in chapter one, in DBR we outline the order and sequence of events as we look for *process oriented explanations*. Prediger, et al. (2015) also stated that design research with a focus on learning must investigate the process of learning.

(b) The second activity was designed to extend the PSSTs exposure to hands-on activities, but to also build on the idea of a closed circuit as well as for them to explain their observations. In the teaching experiment "discussions help the class to reach consensus on conceptual problems and provide feedback to the teacher on the level of student understanding" (Kock, Taconis, Bolhuis & Gravemeijer, 2015: 47). The causal explanation by the students also shows understanding of the observed phenomenon (Heywood, 2007: 522).

The students connect two identical light bulbs in series and then in parallel to compare the brightness of the bulbs. The relative brightness of the bulbs is an indication of the charge flowing per second (i.e. current). The majority of the students across the three cohorts are able to complete this task except where problems arose with equipment. This necessitated using another group's equipment. When they are asked to remove a bulb in each case the issue of a continuous path for the current becomes apparent. In the case of the series combination the break in the loop is obvious while in parallel the bulb still glows. Careful observation of the latter shows a slight increase in the brightness which relates to the internal resistance of the battery. Students must also draw a circuit diagram of the set-up. The idea of how our homes are connected is linked in the discussion about parallel combinations. I offer illustrative examples below of student reasoning when they presented their project models. There are many more instances of where the inquiry in the classroom had a direct bearing on the way in which the students applied their understanding.

Student 3: *"So the resistance decreases in the parallel connection and the current strength increases on the components that are in parallel connection".*

Student 4: *"We have decided to connect our circuit in parallel so that there will be more than one path along which current flow in, in a circuit. For instance if, if one bulb fuse in the circuit the other bulbs can still function, unlike in, in series connection where as one bulb fuse the other one cannot function".*

Student 5: *"We chose to connect it in parallel and not in series because if connected in series it would have pulled too much current and the bulbs would have glowed very dimly".*

These examples are supported by the literature that advocates inquiry-based learning in science to promote conceptual understanding (Hinrichsen, et al., 1999; De Boer, 2006; Smolleck and Nordgren, 2014). The evidence also supports what can be accomplished in a social constructivist learning environment. The teaching and learning occurred through collaboration and experience as the activities were socially negotiated by the students (Murphy, 1997).

(c) As a precursor to the science investigation that examines the factors that influence electrical resistance, the students must first investigate the relationship between potential difference (voltage) and current. This is essentially a verification of Ohm's law as illustrated in Figure 5.1. The conceptual trajectory that is envisaged is highlighted at this point for the purpose of analysis:

- The experimental set-up is designed to familiarise the student with the use of the ammeter and voltmeter and the correct way in which both instruments should be connected in a circuit. Emphasis is also placed on correct reading of the scales on the instruments by checking on each group.
- This is a guided inquiry-based investigation that focuses on basic as well as integrative process skills such as experimenting, controlling variables, interpreting data, etc. (Padilla, 1990).
- Data are tabulated and translated into a graph. Interpretation of the graph establishes that there is a directly proportional relationship between potential difference and current in an Ohmic conductor. Consequently, Ohm's law is defined and the mathematical relationship V/I = R is established.

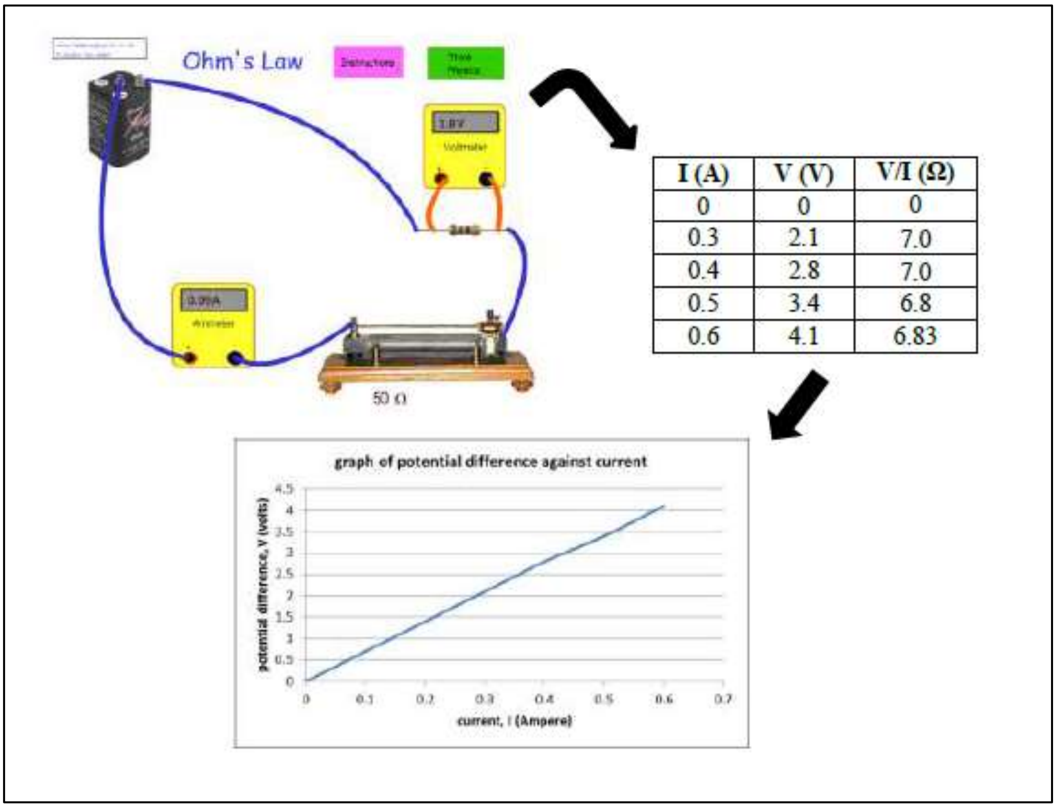


Figure 5.1 Translation of data during Ohm's law investigation

When examining the evidence of the actual trajectory of a student when answering a question on the test relating to Ohm's law as shown below in figure 5.2, the following can be inferred because more than 80.0% of the 2013 cohort answered correctly:

- Engaging in inquiry science allows the students to participate in various activities and develop multiple representations and depth of understanding (Novak & Krajcik, 2006; Harlen, 2015). The students' answers are a good example of their understanding of the concepts.
- The students are able to learn science by linking different representational forms (Prain & Waldrip, 2006), and its disciplinary affordance allows access to disciplinary knowledge (Linder, 2013).
- The integration of the different representations with the written language leads to knowledge building (Nichols, et al., 2013).

- The students developed their process skills by engaging in scientific inquiry to develop their scientific knowledge (Lederman & Lederman, 2012).

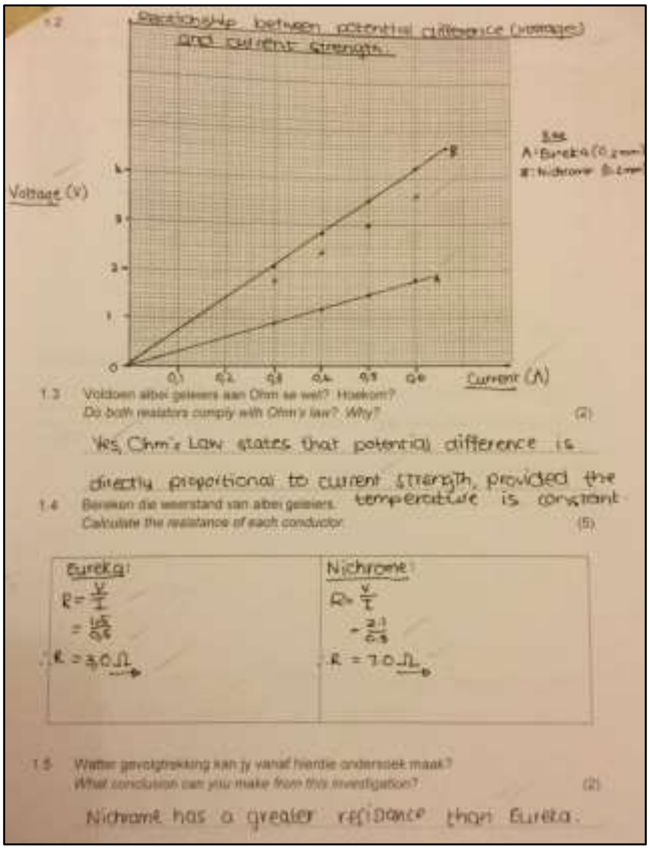


Figure 5.2 A student's answers to an Ohm's law related question

In the next sections I will focus the retrospective analysis on the activities that were formally assessed during the three cycles of the teaching experiment. These also address the research question and sub-questions directly.

5.2 Science investigations

Kock et al. (2015: 49) argued that "students cannot be expected to reinvent theoretical concepts entirely through inductive experimental activities". Science content must be taught and education cannot possibly fulfill its obligation by simply arranging for rediscovery (Skinner, 1987). The science investigation therefore embraced the notion of guided inquiry whereby the problem to be investigated is given and the students must solve it using the apparatus that is provided.

The students are required to investigate the factors that influence resistance except temperature. The apparatus is provided for them to collect the necessary data in groups of four, and they are assisted / guided to ensure that all components are connected correctly. In order to focus the retrospective analysis and place this inquiry-based investigation in a theoretical context, it is important to emphasise the envisioned conceptual trajectory. This also allows for an interrogation of the students' actual conceptual trajectory that is evident in their assessment tasks to show that their understanding is either incidental or contingent upon the science investigation. As Reimann (2011: 44) asserted, "the main thrust of the argument lies in the analysis of the learning trajectories".

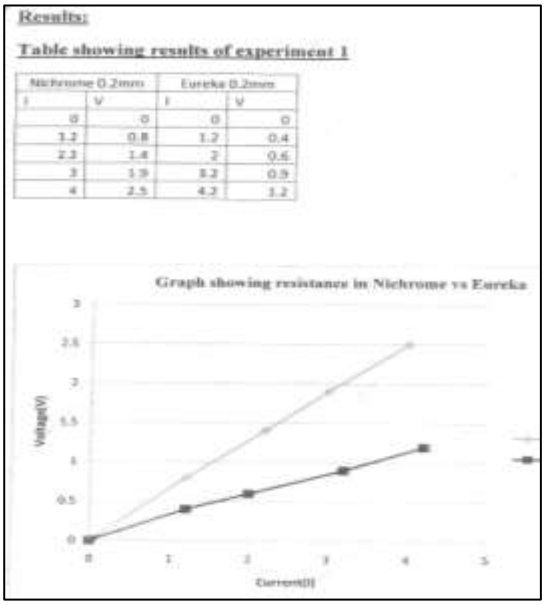
The envisioned conceptual trajectory for the science investigation was as follows:

- Students work in small groups to complete the investigation. This collaborative effort is based on building knowledge in a social constructivist learning environment that promotes discussion (Hyslop-Magison & Strobel, 2008; Enghag, et al., 2013).
- Scientific inquiry is integrated with hands-on opportunities to construct knowledge (Crawford, 2000), particularly in the domain of direct current circuits (Ates, 2005).
- There is a strong focus on developing integrated process skills which extend the basic skills that form the basis for scientific investigation (Martin, 2011).

- The assessed scientific report encompasses multiple representations of the data to develop understanding in the domain (Van Heuvelen, 1991; Prain & Waldrip, 2006; Fredlund, et al., 2014).

(a) Actual conceptual trajectory: Science investigation – 2011 cohort

As indicated in chapter four, the process skills such as hypothesising, tabulating data and graphing were well-developed for this particular cohort of students. Figure 5.3 provides further evidence from a student's scientific report how they are able to translate data from a table into a graph. This is a good example of how multiple representations of the data are used to develop understanding in the domain (Van Heuvelen, 1991). The students are also able to construct their knowledge in the domain through hands-on inquiry which is best illustrated with an example taken from an assessment test. Figure 5.4 shows how a student in this particular cohort is able to hypothesise, deduce and illustrate diagrammatically from a graph of Ohm's law (Ates, 2005; Prain & Waldrip, 2006). This supports the notion that scientific inquiry in a social constructivist learning environment can enhance understanding in the domain of direct current electricity.

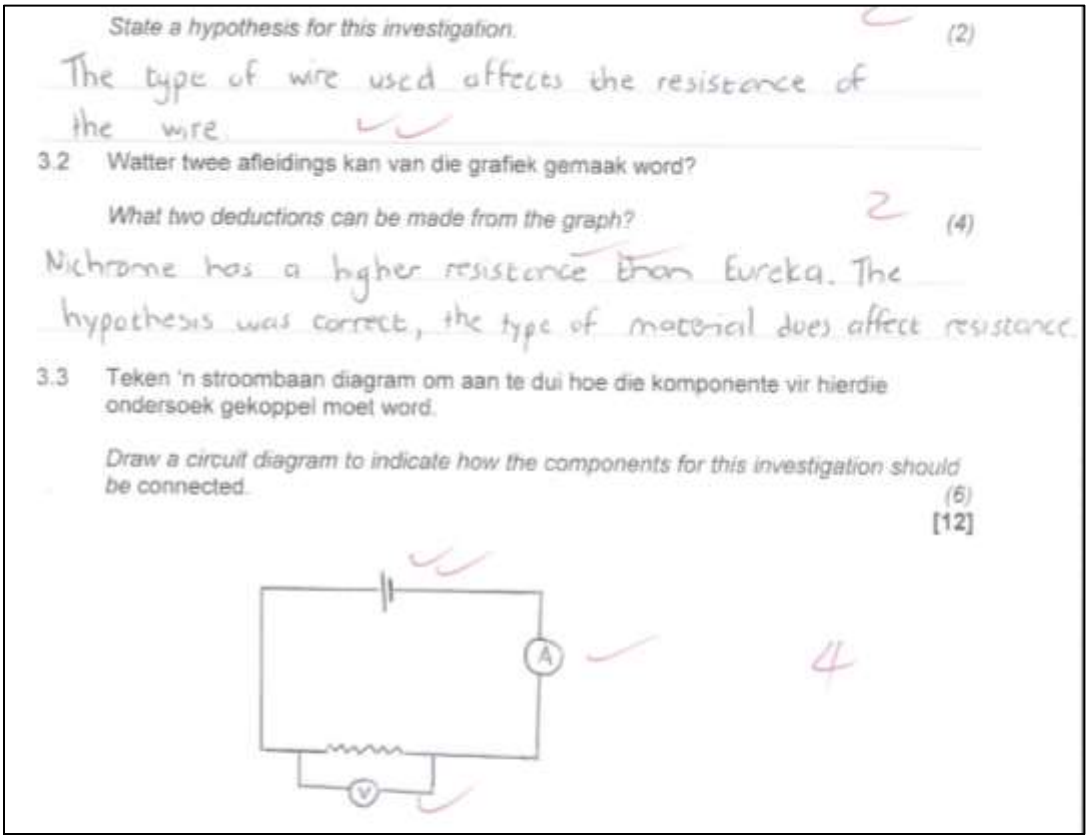


Results:

Table showing results of experiment 1

Nichrome 0.2mm		Eureka 0.2mm	
I	V	I	V
0	0	0	0
1.2	0.8	1.2	0.4
2.2	1.4	2	0.6
3	1.9	3.2	0.9
4	2.5	4.2	1.2

Figure 5.3 **A table and graph taken from the scientific report of a student in 2011**



State a hypothesis for this investigation. (2)

The type of wire used affects the resistance of the wire

3.2 Watter twee afleidings kan van die grafiek gemaak word?

What two deductions can be made from the graph? 2 (4)

Nichrome has a higher resistance than Eureka. The hypothesis was correct, the type of material does affect resistance

3.3 Teken 'n stroombaan diagram om aan te dui hoe die komponente vir hierdie ondersoek gekoppel moet word.

Draw a circuit diagram to indicate how the components for this investigation should be connected. (6)

[12]

Figure 5.4 **An answer on the assessment test showing multiple representations of a student in 2011**

The 2011 cohort demonstrated poor integration process skills (Padilla, 1990) because the majority (79.0%) are unable to interpret the data, and their ability to draw good conclusions is average. Figure 5.5 below is an example of a poor conclusion as the student fails to state how the different factors affect the resistance.

> According to results, as the current increased, so did the potential defence of the circuit which produced a fairly even reading for the resistance in each circuit. Thickness, length and density affected the resistance of the circuit as predicted in the hypothesis

Figure 5.5 A conclusion taken from the scientific report of a student in 2011

(b) Actual conceptual trajectory: Science investigation – 2012 cohort

The data presented earlier in chapter four clearly identified well-developed overall skills, but a feature of this particular cohort is also their inability to interpret data adequately which is evident from the 63.0% who fall in this category. Kanari & Millar (2004: 767) concluded in a study that students at a young age are able to acquire competence when investigating the relationship between two variables. However, when the patterns between the data are less obvious then students tend to struggle. Graph interpretation and analysis involve more complex processes to see the relationships implicit in the graph and requires deep understanding to compare patterns (Wainer, 1992; Shah, Mayer & Hegarty, 1999; Friel, Curcio & Bright, 2001). This possibly explains the students' poor understanding when it comes to analysing and interpreting graphs.

(c) Actual conceptual trajectory: Science investigation – 2013 cohort

It would appear that this particular cohort had certain factors that seem to have contributed to a deeper, well-developed understanding of science investigation. Upon reflection the classroom culture was one in which more questions were asked, and a good rapport was established with the students. The students extended this beyond normal class time to seek clarity on what they need to complete their scientific report. However, this does not detract from what would seem to be good process skills, basic and integrated, on their part. This is evident from the report of two students shown in Figures 5.6 & 5.7 respectively below. Their answers show that they are able to see the complex relationships implicit in the graphs by producing incisive analyses and conclusions.

Analysis

According to my findingsNichrome produces a large current than equal length of Eurika wire of the same thickness. Eurika wire thus has a large resistance. Longer length of conductor (wire) has a higher resistane and has a smaller current flow because four length of 0.4mm Nichrome has smaller current compared to 2 length of the same conductor (wire).

Conclusion

According to my findings my hypothesis was true. Resistance is influenced by the type of material, length and diameter and that current is inversely proportional to resistance because if a conductor has a higher resistance the current that will flow on that conductor will be smaller than that of a smaller resistance. The length of the wire also influence the resistance because once the length is long it makes the resistance to be higher and cause smaller current to flow and that means that the length is directly proportional to resistance.

Figure 5.6 An analysis and conclusion taken from the scientific report of a student in 2013

Conclusion:

In the case of the different cross sections, the circuit which had the metal (Nichrome) with the larger diameter of 0.4mm had an increased current which proves that the circuit with the larger diameter has less resistance.

In the case of the different types of metals the Eureka allowed a greater resistance than that of the Nichrome. This proves that with Eureka in the circuit there is less resistance and a higher current.

With the results read at different lengths of metal, one can see, that the shorter the length of the circuit the higher the current. Therefore this proves that the shorter the length there would be less resistance because of the increase in current.

In conclusion one can say that resistance is in fact influenced by cross section, lengths and types of metal. That within this investigation, in all cases the above mentioned influence increase the flow of current and therefore decreases the effects that resistance has on the circuit.

Figure 5.7 A conclusion taken from the scientific report of a student in 2013

5.3 Problem-solving

In this part of the retrospective analysis I motivate the theoretical framework in which problem-solving is placed, and analyse the students' answers in relation to this framework. The idea is to engage the students with higher-order problem-solving questions that are linked to the notion of a "big ideas" constructivist (Traianou, 2006; Murphy, 1997). These activities are also designed to be "transformative and sets high learning demands to challenge the learner during problem-solving" (Hyslop-Magison & Strobel, 2008). Students' conceptual understanding and problem-solving skills are also enhanced if the activities are research-based (Fraser, et al., 2014). In the domain of direct current electricity it is important that students are able to do qualitative and quantitative reasoning (McDermott, et al., 2000).

The envisioned conceptual trajectory for problem-solving based on the electricity assessment test was as follows:

- Test student understanding of a closed circuit.
- Test student understanding of current and potential difference.
- Test student understanding of series and parallel combinations in a circuit.
- Expect students to solve problems using Ohm's law.
- Students must use quantitative and qualitative reasoning.
- Students must answer a question on multimodal representations to show their understanding.
- Students must apply their knowledge to predict and explain the direction of a magnetic field around a conductor (only included in 2011 assessment).

(a) Actual conceptual trajectory: Problem-solving – 2011 cohort

All of the multiple-choice questions required that the students reason qualitatively to substantiate their response. The first question built on a science investigation done in class, but it would appear that the majority of the students reasoned that by removing a light bulb in parallel it follows that more current can flow in series. They appear to adopt sequential reasoning (Duit & von Rhöneck, 1997). The second question received the most correct responses, but the 19.0% who incorrectly responded that D is the answer deserve some explanation. It seems that these students adopt a consumption model of current in that the first light bulb consumes energy and leaves less for the second bulb. Interestingly, 14.0% of the students failed to explain their correct answer which supports the view that qualitative reasoning is lacking (Van Heuvelen, 1991). The third question was poorly answered with no discernible pattern emerging. This does point to the students' inability to apply reasoning when elements within the circuit change. In this instance a resistor was added in parallel which lowered the resistance and increased the current. However, the students apply local reasoning by failing to look at the rest of the circuit (Duit & von Rhöneck, 1997). On the fourth question 43.0% responded incorrectly that A is the answer which showed that they realise that the current splits in parallel, but failed to see that the potential difference is the same across the combination. A significant 16.0% also failed to substantiate their answer correctly. The last multiple-choice question was very poorly answered with the majority (35.0%) reasoning incorrectly that the current is less because the resistance has increased. They failed to see that the potential difference and resistance has the remained the same and therefore the current is the same. These results all support the findings of McDermott and Shaffer (1992) that students are unable to reason qualitatively about the behaviour of an electric circuit.

In the circuit problem the majority (78.0%) of the 2011 cohort are able to apply a basic formula (I = V/R) to calculate the current in the parallel combination. However, 75.0% are unable to deduce the current in the main circuit in relation to the combination. That is, they fail to reason that they need to find the current that has split and simply add the two. This is illustrated in Figure 5.8 below. About 50.0% of the students determined the potential difference correctly. Liégeois, et al. (2003) has argued that students tend to confuse the term potential difference because of their everyday experiences of the term. The students' inability to reason qualitatively again comes to the fore in the last two questions as shown in Figure 5.9. McDermott and Shaffer (1992) argued that being able to solve quantitative problems is no guarantee of conceptual understanding as students are unable to answer qualitative questions based on the same concepts. These results underscore their findings which show that problems in this domain persist.

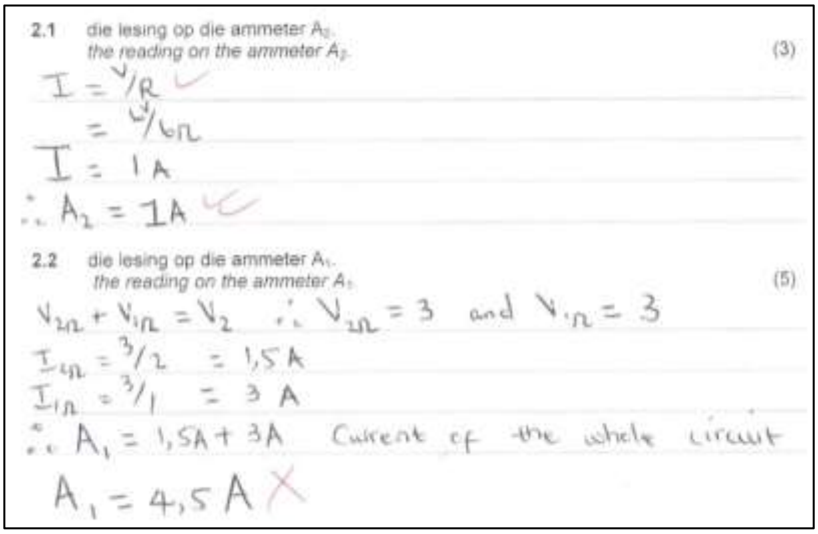


Figure 5.8 **A students' incorrect answer to question 2.2 on the test in 2011**

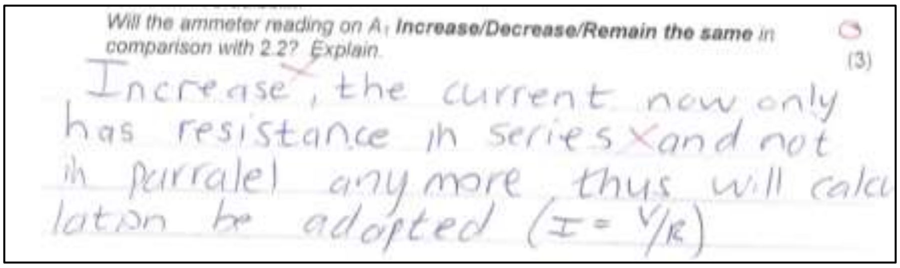


Figure 5.9 **A students' incorrect qualitative reasoning on the test in 2011**

The multimodal question on the test is dealt with in section 5.4 (a) below. The final aspect of the test in this retrospective analysis deals with the question of the motor-effect. The magnetic effect of a straight current-carrying conductor was practically investigated in class. The questions on the test was simply an application of this, but the students did poorly because 67.0% and 71.0% respectively could not recognise a diagrammatic representation of the magnetic effect and give an explanation for it. These students have failed to recognise a big idea even though they were exposed to it within an inquiry-based classroom (Harlen, 2010).

(b) Actual conceptual trajectory: Problem-solving – 2012 cohort

The idea was to persist with the same questions as for the 2011 cohort for the assessment, except for removing the motor-effect question because this was not dealt with in class. The focus had shifted to allow more time for the students to present the evidence and explanation for their project model.

The same pattern of responses obtained with the 2012 cohort on the multiple-choice questions. However, they fared better on the first question which might be interpreted as them having benefitted from the exposure to the hands-on engagement with the concepts (Crawford, 2000; Küçüközer & Demirci, 2008). A significant number (43.0%) of the students also failed to look at the circuit as a whole when they responded with B as the correct answer on the third question. These students also fared poorly when they had to apply qualitative reasoning on the last two questions.

At this point of the analysis with regard to problem-solving it might be useful to indicate straightforward examples that were given to reinforce certain concepts. Figure 5.10 below shows how for the same two light bulbs in series and in parallel (diagrams 1 & 2) the current differs – in fact each bulb has double the amount of current in parallel. This follows from the hands-on investigation and goes further by showing that in parallel the current is doubled if the resistance is halved (diagram 3).

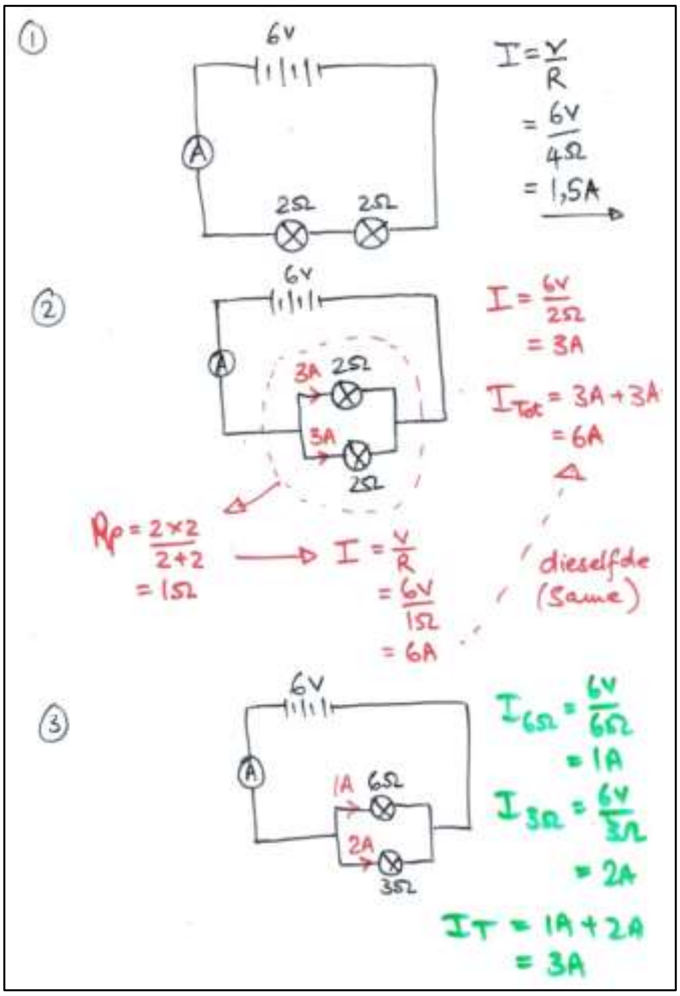


Figure 5.10 An example of an explanation of current splitting in parallel

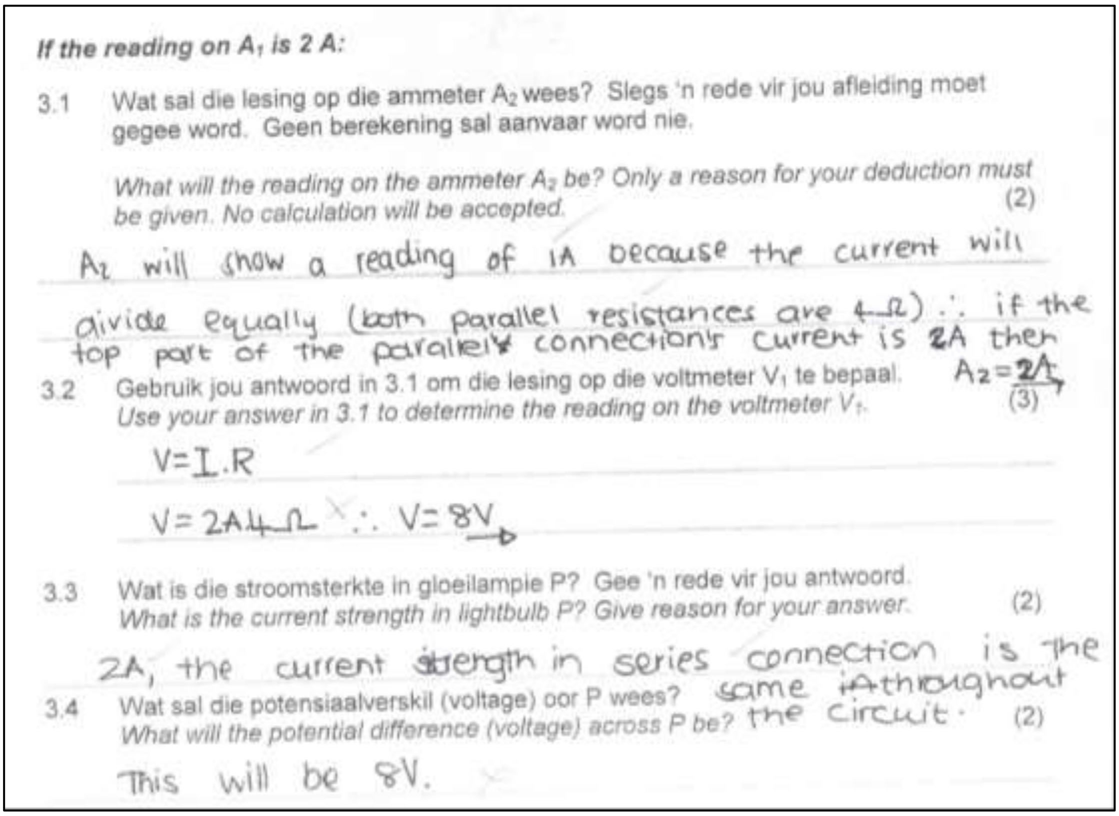
This cohort was also able to answer the routine question correctly (95.0%), but 70.0% are unable to make simple deductions as far as the current splitting in parallel is concerned. These students do not have the necessary conceptual understanding as far as finding solutions to numerical problems are concerned (Mullis, et al., 2003). The rest of the quantitative and qualitative questions were very poorly answered and reinforced what has been said before.

(c) Actual conceptual trajectory: Problem-solving – 2013 cohort

All the multiple-choice questions were designed to reinforce the fundamentals about current, potential difference and resistance in series and parallel circuits. Coupled to this were the instruments such the ammeter and voltmeter and a qualitative understanding of what they measure in the electrical circuit. While the overall achievement of this group was commendable, there are areas that need to be highlighted. The first multiple-choice question was very straightforward, but 18.0% of the students did not understand how a parallel combination lowers the effective resistance in a circuit. These students find the concept problematic and thus reason incorrectly (Duit & von Rhöneck, 1997). On the second question 18.0% of the students failed to see the inversely proportional relationship between current and resistance by choosing D as the correct answer. About 20.0% of the students still have an incorrect understanding of potential difference (Liégeois, et al., 2003). They do not realise that the voltage across the parallel combination is the same in the fourth question.

The circuit problem was also well-answered, but a few pertinent comments must be made in the retrospective analysis. About 27.0% of the students could not deduce what the current in the parallel combination would be given that it should divide equally in this case. The students are also unable to calculate the potential difference when 75.0% got the wrong answer, and their qualitative reasoning about potential difference is also flawed. While this group has demonstrated conceptual understanding, some areas are still problematic and these are generally supported by the literature in the domain.

Figure 5.11 is an example of a student's answers which illustrate the latter point.



If the reading on A_1 is 2 A:

3.1 Wat sal die lesing op die ammeter A_2 wees? Slegs 'n rede vir jou afleiding moet gegee word. Geen berekening sal aanvaar word nie.

What will the reading on the ammeter A_2 be? Only a reason for your deduction must be given. No calculation will be accepted. (2)

A2 will show a reading of 1A because the current will divide equally (both parallel resistances are 4 Ω) ∴ if the top part of the parallel connection's current is 2A then A2 = 2A

3.2 Gebruik jou antwoord in 3.1 om die lesing op die voltmeter V_1 te bepaal.
Use your answer in 3.1 to determine the reading on the voltmeter V_1. (3)

V = I.R

V = 2A 4 Ω ∴ V = 8V

3.3 Wat is die stroomsterkte in gloeilampie P? Gee 'n rede vir jou antwoord.
What is the current strength in lightbulb P? Give reason for your answer. (2)

2A, the current strength in series connection is the same throughout the circuit.

3.4 Wat sal die potensiaalverskil (voltage) oor P wees?
What will the potential difference (voltage) across P be? (2)

This will be 8V.

Figure 5.11 A student's answers to the circuit problem in 2013

5.4 Multimodal representations

The concept of multiple representations in physics education has been well-researched. The conjecture in this study to engage students in inquiry-based science is linked to the notion of giving them opportunities to be exposed to multiple representations of the data during science investigations as well as during teaching. Physicists rely on qualitative reasoning and multiple representations (Van Heuvelen, 1991) whereas students lack the skills to do this. The student must be able to conceptually link the different representations to learn and understand concepts (Prain & Waldrip, 2006). As indicated in chapter two the affordances of multiple representations to disciplinary knowledge depends on the learning environment

(Linder, 2013; Enghag, et al., 2013). When models, graphs, tables and diagrams are integrated with the verbal and written language it leads to meaning-making (Nichols, et al., 2013).

The envisioned conceptual trajectory for the students' multimodal representations was as follows:

- Students must engage in translation activities which include the experimental mode, descriptive mode (tables, graphs & verbal), mathematical mode, and figurative mode (diagrams).
- These activities will include hands-on investigations to familiarise themselves with connecting various components in a circuit and drawing circuit diagrams.
- Formal assessment opportunities will test their understanding of the above.

(a) Actual conceptual trajectory: Multimodal representations – 2011 cohort

The question on the assessment test required of the students to translate from a graphical representation to produce a hypothesis, make deductions and give a diagrammatic representation of the scientific investigation. Less than 50.0% are able to state a hypothesis in which the variables under investigation are properly identified. A translation skill such as making a deduction requires higher-order thinking. About 70.0% of the students are unable to do this which shows that there is perhaps a need for more explicit teaching in this regard. It would seem that a diagrammatic representation has been reasonably mastered by this cohort. The students are unable to make all the conceptual links between the various representations (Prain & Waldrip, 2006) and do not integrate representations such as graphs with the written

(Nichols, et al., 2013). This appears to be an impediment to them acquiring the disciplinary knowledge in the domain of direct current electricity.

(b) Actual conceptual trajectory: Multimodal representations – 2012 cohort

During the assessment test this cohort showed that a large proportion (>60.0%) of them are unable to draw diagrams to demonstrate an understanding of science concepts and relationships. They are unable to extract information and provide explanations to show that they understand the underlying law or theory (Mullis, et al., 2003). Bernhard and Carstensen (2002) maintained that students fail to connect concepts and representations after traditional instruction. Sengupta and Wilensky (2011) also made the point that students are unable to relate the behaviour of charges at a microscopic level to what they observe at a macroscopic level. This cohort has shown that perhaps more needs to be done to reinforce these concepts during inquiry-based teaching in the Vygotskian sense by challenging them to think beyond the surface.

(c) Actual conceptual trajectory: Multimodal representations – 2013 cohort

The multimodal question in the assessment test required that students translate tabular data into a graph, state a hypothesis and draw a conclusion from the investigation. They must also calculate the resistance and draw a circuit diagram for the experimental set-up. The results in chapter four showed that on average more than 80.0% of the students were able to correctly answer the translation questions. Their graphing skills were particularly good which showed an ability to integrate the different representations to make sense of the data (Nichols, et al., 2013). It is also noteworthy that this group displayed better overall translation skills than the 2011 and 2012 cohort of students. Whether this is contingent upon what had gone before in the social constructivist learning environment is supported by the evidence of their performance in the science investigation. This group's process skills were also above average which leads to the conclusion that they benefitted from exposure to multiple representations in the physics environment (De Cock, 2012). Their ability to extract information shows that they have developed conceptual understanding (Mullis, et al., 2003).

5.5 Argumentation

Students must be engaged in discussion and argumentation to attain higher levels of conceptual understanding (Liang & Gabel, 2005). Discussion and explanation is one of the hallmarks of scientific inquiry and the social constructivist learning environment fosters this as a goal. When students exchange ideas they learn from each other and also acquire the discursive practices of scientists. Argumentation is also a skill that involves reasoning, evidence and claims (Barak & Dori, 2009). These are skills that can be acquired in an inquiry-based classroom (Martin & Hand, 2009). In this study students were placed in contexts that value evidence when they presented their project model. In particular, the appropriateness and sufficiency of the evidence that they present was assessed (Berland and McNeill, 2010).

The envisioned conceptual trajectory for the students' argumentation products was as follows:

- When the students engage in science investigations in small groups they must discuss and reach consensus before presenting an explanation for their observation.
- Students must work collaboratively as they design their project model. They must produce an explanation of how and why their model functions (Schwarz, et al., 2009).
- The students demonstrate conceptual understanding when they produce a model to show understanding of science concepts, relate knowledge to the physical concepts observed, explain and illustrate with examples (Mullis, et al., 2003).

(a) Actual conceptual trajectory: Argumentation – 2011 cohort

In order to do a retrospective analysis of how the students' reasoning was classified based on the evidence they presented by way of their model, some direct quotes are taken from the transcripts. The extent of their understanding is also established when they explain the underlying basic principles of direct current electricity.

Student 6: "The reason for the current that flows is that it is connected from positive to negative and we chose the method because such a scientific method connection allows it to flow from positive to negative and work".

The evidence presented was appropriate, but the reasoning to explain the model was inaccurate. The evidence and reasoning was deemed to be of a low complexity level.

Student 7: *"The two batteries we are using is our circuit supply of the energy source. The two light bulbs over here are connected in parallel which allows equal amount of energy to be applied in both of the batteries. It also means that there is an equal brightness in both".*

The evidence presented was appropriate, and the reasoning to explain the model was accurate. The evidence and reasoning was deemed to be of good complexity level.

Student 8: *"The current does not split because it is connected in series and the lights shine at equal levels. And it flows from negative to – positive to negative".*

The evidence presented was appropriate, and the reasoning to explain the model was moderate. The evidence and reasoning was deemed to be of moderate complexity level.

Almost 46.0% of the students in the 2011 cohort produced appropriate and sufficient evidence and reasoning that was considered to be scientifically accurate and complex. These students have the necessary argumentation skills since they can substantiate their claims (Barak & Dori, 2009). They have also demonstrated conceptual understanding by linking their model to the underlying science concepts. It is the approximately 41.0% whose skill levels are moderate who could possibly benefit from greater exposure to more accurate framing of an argument through teacher-guided discussion (Liang & Gabel, 2005). However, Sampson and Clark (2008) have also said that justifying an explanation through argument is also difficult for students. There should be a measure of persistence as it helps students to engage with the social construction of scientific ideas (Bricker & Bell, 2008). The following excerpt from the transcript shows that students are able to integrate their knowledge through exposure to inquiry-based science:

Student 9: *"If it is in parallel the other one can still work, and these two in series – if you take it out then the other one dies. So it's just a representation that if one, say, fuses in series then the rest won't work. But in parallel the rest will still work. And yes, another reason why it doesn't work well is we used very thin wire, which means that the current – agh there is more resistance so the current doesn't flow very strongly, there is less current".*

(b) Actual conceptual trajectory: Argumentation– 2012 cohort

This particular cohort demonstrated poor argumentation skills with the following being the only example where appropriate and sufficient evidence and reasoning of a good quality was produced:

Student 10: *"It is the source that provides energy for the flow of current. It is connected in parallel because the current is spread evenly. Thus, the light bulbs will glow with the same brightness. We chose to connect it in parallel and not in series because if connected in series it would have pulled too much current and the bulbs would have glowed very dimly. And if the one bulb obviously is disconnected then the other one will still be glowing".*

A large proportion (40.0%) produced argumentation products which were moderately complex, while altogether 55.0% produced inaccurate or no reasoning. The instructions were quite explicit in terms of explaining the model using principles of electricity to demonstrate conceptual understanding (Mullis, et al., 2003). Their poor performance can possibly be linked to the students' poor qualitative reasoning skills which were also evident when then they did problem-solving.

(c) Actual conceptual trajectory: Argumentation– 2013 cohort

This particular cohort demonstrated good conceptual understanding of the underlying principles when they explained the functioning of their model (Mullis, et al., 2003). A typical example taken from the 53.0% who demonstrated good argumentation skills is seen in the next extract from the transcript:

Student 11: "We can observe that both the bulbs will shine equally – have equal brightness. If we had an ammeter reading it will be the same everywhere in the circuit. In the series circuit if there is a break in connection - a bulb blows or something there is an interrupted flow of energy. None of the other things will work. If we were to add another bulb or motor there will be an increase in the total resistance which means the total current would decrease – that is an indirectly proportional relationship".

This is another example of how conceptual understanding can be developed when the students link their explanation to the science investigations they were exposed to. There is still a significant proportion whose argument skills need to be sharpened. As indicated earlier, it is not an easy skill to master and greater exposure could improve students' skills (Liang & Gabel, 2005; Sampson & Clark, 2008)

Colwell and Reinking (2013: 479) had the following to say about the retrospective analysis:

> The intent was to integrate our findings, drawing conclusions about pedagogical theory and generating pedagogical principles and recommendations that might guide practitioners and future researchers.

I conclude this chapter with a final reflection of the three cycles of the teaching experiment.

5.6 Final reflection

The iterative cycles of the teaching experiment across the three cohorts were characterised by the same type of assessment tasks and activities with a few minor adjustments as the need arose. The conjecture that underpinned the teaching experiment remained intact, i.e. inquiry-based science could enhance the PSSTs conceptual understanding in the domain of direct current electricity. At the end of the first cycle it was clear that the students perhaps need more time with the design of their project model. This was facilitated through time that was made available outside the normal teaching time. These opportunities also gave students a chance to refine their models. The practical activity relating to the motor effect was also removed as this was not a key focus. It was more important that students develop their reasoning skills and so an emphasis was placed on facilitating more discussion in class. The assessment test at the end of the second cycle was the same as the first except for the motor-effect question that was removed. During the third cycle I went back to emphasising the basics and making sure that students could apply the principles of direct current electricity. As stated in reflections after the previous cycles, there was a need to integrate direct instruction strategies. Robertson (2007) has argued that it is sometimes difficult to impart content knowledge using inquiry methods. It is also easier to guide students during problem-solving by showing steps to solve the problem. A major concern had been students' qualitative reasoning on some assessment test items during cycles 1 and 2. I therefore set new questions for the assessment test with the 2013 cohort that emphasised the basics of direct current electricity.

The final chapter will summarise the findings of the teaching experiment, make recommendations for future research and draw conclusions about the domain-specific learning environment.

CHAPTER 6

SUMMARY, RECOMMENDATIONS AND CONCLUSION

We live in a globally competitive world in which access to information is available at the click of a button. I had an interesting observation recently which showed how children, Grade 4 learners in this case, are growing up in a digital age. The PSST was doing a lesson on the solar system and asked which planet is the warmest planet. Common sense will dictate it is the planet closest to the sun, which is Mercury. A learner commented that it is in fact Venus and a Google search revealed this to be true. The reason is that Mercury has no atmosphere to trap the radiation whereas Venus has an atmosphere. The PSST was giving a very interesting lesson, but did not appear to falter as she handled the situation very competently. The point is that as teachers we do not know everything, but the least we can do is to have the tools at our disposal to handle these tacit moments that will certainly arise in the classroom environment.

6.1 Summary

This study started with a conjecture that an inquiry-based science teaching strategy in a social constructivist learning environment will foster the development of PSSTs conceptual understanding of direct current electricity. It proposed that a transformative conjecture-driven teaching experiment which uses a DBR approach would help to achieve this goal. Further, it set out to design a domain-specific learning environment to help accomplish this goal. The nature of design research is not to establish causal relations as in classical experimental research, but to document the sequences and scaffolding of the teaching and assessment tasks.

These thick descriptions allow for context-specific generalisations which can be adapted to other teaching and learning environments. Plomp (2013: 26) put it more pertinently by stating that "the practical contribution of design research lies in developing empirically-grounded prototypical learning trajectories that may be adopted and adapted by others". The conceptual understanding of the student that has been explored in this study can be said to be more idiographic in nature. This implies that the focus is on probing the complexity of understandings of a concept by using quantitative and qualitative methods.

The adoption of a DBR approach in this study was not accidental, but motivated by a sincere desire to do research at the coalface of practice as it were. A better understanding of this emerging methodology developed through reading of the literature which has become more detailed in the last few years. This also went along with a parallel reading of physics education research which highlighted the problems of students, at school and university level, in different content domains such as mechanics, optics, etc. The research revealed possible areas of remediation, but the research studies always appeared after the fact. This is why DBR through its iterative cycles of design, allowing for refinement of solutions in practice after reflection, was so appealing.

It has also been argued in this thesis that science teacher education in South Africa is in urgent need of reform to address the shortcomings of our teaching corps. Traditionally we come from a didactic expository approach to teaching and learning by which we treated students as empty mental slates to be filled with information. The adoption of an inquiry-based approach in this study has been strengthened by a recent statement in which it is indicated that inquiry-based pedagogy has been widely embraced in science education (Harlen, 2015). In chapter two it was shown that Deweyan pragmatism was the ideal philosophical framework to underpin DBR in science education. It integrates theory with practice through application of the knowledge we gain during interaction in our environment. This has been aptly demonstrated in the teaching experiment through iterative cycles that were refined upon reflection at the end of each cycle.

The importance of developing the students' process skills in a social constructivist learning environment was also highlighted from the literature. Ample evidence from the students' work support this notion, albeit that the level of basic and integrated skills vary across the board. For example, most students are able to formulate, design and build a physical model of a basic electric circuit, but not all of them are able to give a scientifically appropriate explanation of how it functions. A review of the literature about the teaching and learning of electricity also revealed that not much has changed over the last 30 years in terms of student understanding of the key concepts in the domain. Problems persist with regard to understanding of current, potential difference (voltage) and resistance. The emphasis on quantitative problem-solving has come at the expense of the development of students' qualitative understanding and reasoning about electric current.

The latter prompted an exploration of pedagogical strategies that would address the development of PSSTs conceptual understanding of direct current electricity by moving away from a formulaic approach. These were also supported by the literature which accentuated the following:

- In order for students to develop their understanding of science concepts they need to understand scientific models. Science is about exploring the world around us and the key to being able to explain our observations lies in the utilisation of these models. Electric current, for example, is not visible to the naked eye but manifests itself in the transformation of electrical energy into light, heat and kinetic energy. Thus we use the scientific model to explain what happens when these invisible charges move.
- This leads to an understanding of the different ways in which concepts are represented in science. Linked to the development of process skills indicated earlier are the development of multiple representations and the ability of the student to translate from one form into another. These entail the experimental, tabular, graphic, verbal, and mathematical modes to develop conceptual understanding.
- Students must be able to solve electric circuit problems by applying Ohm's law. However, the development of higher-order thinking skills must be carefully cultivated through graded problem sets that address different cognitive levels and ultimately extend into the students' ZPD.
- The inquiry-based classroom encourages discussion and dialogue to explain concepts. This is linked to the notion of developing the students' argumentation skills by giving them opportunities in their learning environment. During the teaching experiment ample opportunities were given to the students to work collaboratively to develop their argumentation skills.

- Science investigations allow the students to develop a range of skills such as formulating a hypothesis, designing a procedure, collecting and analysing data, and drawing conclusions.

Before outlining the key findings of this study, it is important to summarise the methodological aspects of the DBR teaching experiment adopted in this study and what it allows one to do. A relevant reminder which was quoted in chapter 3 is that DBR “aims both at developing theories about domain-specific learning and the means that are designed to support that learning” (Bakker & van Eerde, 2015: 430). It is the development and validation of students’ conceptual understanding of direct current electricity that was explored through the transformative conjecture-driven teaching experiment (Confrey and Lachance, 2000). The dual emphasis on content and pedagogy stems from the conjecture which drives the process. What emerges is an envisioned conceptual trajectory which is navigated through activities and assessments in the content domain by means of various pedagogical strategies. Successful navigation leads to the actual conceptual trajectory which is the learning and understanding of concepts in the domain. Evidence of this is taken from student records of assessments, both written and verbal.

6.2 Key findings

(a) General findings

- When doing a teaching experiment using a DBR approach it is important to do a preliminary study to investigate the content and pedagogy and how students adapt to what might be perceived to be a deviation from the norm. Any radical change from the learning environment which students are used to might be opposed unless it is infused into the classroom culture beforehand.

Students became used to my approach already at a first-year level when I emphasise an integration of theory and practice.

- A guided inquiry-based approach works best because one cannot expect students to reinvent theoretical concepts (Kock, et al., 2015). Essentially, what we are trying to accomplish is the development of students' understanding of concepts that are already well-established. For example, investigating Ohm's law is merely a verification of the law and not a discovery of the law. In the process students acquire certain process skills and develop their conceptual understanding. In this study I was interested in the different pedagogical pathways that lead to a fruitful achievement of this goal.
- All envisioned (anticipated) conceptual/learning trajectories must be carefully planned with the necessary working equipment if practical activities are to be engaged in. Practical investigations must serve as a means to accomplish the goal of developing conceptual understanding and not be a hindrance to reach this goal.
- Any unintended/unanticipated consequences of collaborative work should be firmly dealt with. For example, students work together as far as possible to complete their investigations to collect data. This collaboration does not extend to submission of the same written scientific reports that must be assessed.

(b) Specific findings relating to the sequence of events

- The first activity to establish the idea of a closed circuit is important as it manifests itself in many subsequent activities or assessments. It is important to reflect on student thinking and link it to existing models in the literature.

Depending on the students' level of exposure to practical activities it is necessary to be interactive and engage with the students to assist them where necessary. This activity should culminate in a clear exposition of what is required for current to flow in a circuit which is underscored by an explanation of what is happening at a microscopic level. Students are subtly introduced to big ideas whereby any observable phenomena must have an explanatory model. Using a simulation programme on the computer could help to reinforce this concept.

- The second activity extends the notion of a closed circuit to series and parallel combinations of light bulbs. The relative brightness of the bulbs is compared to give an idea of the charges flowing per second, i.e. the idea of current is introduced. Students must also give an explanation as to why the same two light bulbs are brighter in parallel compared with series. This can be linked to the analogy of water flowing in a thin versus a thick pipe. Removal of a bulb in each case also reinforces the idea of a complete pathway for current to flow. This experimental activity is translated into a diagrammatic representation which embraces the concept of multimodality.
- The next activity is an investigation of Ohm's law which entails more exposure to practical investigations. Students are orientated to the correct way of connecting an ammeter and voltmeter in an electrical circuit. This activity allows for translation of tabular data into a graph, interpretation and formulation of Ohm's law into words as well as a mathematical representation. It also leads to an understanding of resistance in an electrical circuit. The evidence of students' assessments, especially the 2013 cohort, has shown

that guided science investigations do help to promote their conceptual understanding of direct current electricity.

- An investigation into the factors affecting resistance follows from the Ohm's law investigation. This allows for the further development of students' process skills such as hypothesising, interpreting and drawing conclusions. The evidence of students' scientific reports shows that across the three cohorts in the teaching experiment the students acquired a fair to a very good understanding. More importantly, these skills that they acquired as a result of engaging in hand-on investigations benefited them to the extent that some showed a good understanding of these concepts in the assessment test. For many, however, interpretation skills still appear to be lacking.
- As far as problem-solving skills are concerned most of the students are able to do lower-order questions. When higher-order thinking is required to solve quantitative and qualitative problems they are found lacking. An area of concern relates to parallel combinations where important principles that were dealt with in detail, such as current dividing while the potential difference remains the same, are still not well understood.
- The multimodal skills that students demonstrated varied across the three cohorts. It would seem that translating data from a tabular form into other forms such as a graph is fairly straightforward. When students are given a graph to interpret and formulate a hypothesis for the investigation they appear to show a poor understanding.
- Students must be given opportunities to engage in argumentation whereby they present evidence to substantiate a claim that they make. Some appear

to have benefited from exposure to inquiry-based science when they use good reasoning skills they acquired during guided science investigations. However, many still lack appropriate scientific reasoning skills that demonstrate a good conceptual grasp of the underlying principles of current electricity.

It is evident from the poor performances of the 2011 and 2012 cohort of students on the electricity test that traditional instruction approaches should complement the inquiry-based teaching strategy to explain certain concepts. Problem-solving of electric circuits by the traditional lecture method could improve students' achievements (Marshall & Dorward, 2000). In addition to content knowledge which is taught through direct instruction, teachers should help students to develop process skills which are gained by learning through inquiry activities (Wang & Wen, 2010). This speaks to the importance of striking a balance between the different approaches.

6.3 Recommendations for further research

It has been argued that design-based research cannot be generalised. In this study the domain-specific environment has been described in detail. This allows for the possibility of the learning trajectories to be adapted and adopted in another setting. It would also broaden the validity of design studies which generally seeks ecological validity.

The study was confined to the study of direct current electricity. It would be interesting to see how the participants would develop in another topic using DBR.

Gender differences would also be an interesting angle to explore because generally more females are enrolled in the education programmes.

It has been assumed that the participants in this study had the same background exposure to science. An interesting study would be to look at how their backgrounds influence the development of their conceptual understanding in the domain.

Would the students benefit from more explicit teaching of argumentation? How will this impact their understanding of concepts? This is an avenue that could be explored by focussing on formulation of evidence to substantiate claims.

The students' process skills were also assumed to have been sufficiently developed before their second year of study. It might be informative to establish their actual levels before commencing the teaching experiment.

6.4 Conclusion

There is widespread concern about the effectiveness of our education system which can basically be classified as comprising two extremes. Those learners who have the social and cultural capital can have access to a world-class education because there are schools with the best resources that abound in South Africa. However, the majority do not have access to quality education due to a lack of resources. These differences are more pronounced in science related subjects where access to well-equipped laboratories is few and far between. Teachers who have the necessary pedagogical content knowledge can make a difference even under these trying circumstances. It requires some innovative approaches which are student-centred and show an aversion for traditional rote learning methods (Agrusti, 2013). This should also be coupled with a clear focus on core ideas that are embedded within the curriculum.

Universities play a critical role in delivering teachers who have the necessary skills to bring about the changes in pedagogy in the classroom that would ensure that all learners have access to a quality education. The school science curriculum is vast and little emphasis is placed on developing a deeper understanding of concepts. We therefore need teachers who can explain concepts in a manner that the learners can not only make sense of it, but also develop a good conceptual understanding. The question is therefore to what extent can this study make a contribution to this goal of producing competent science teachers? I want to relate these to theories about domain-specific learning and the means to support that learning in the context of teaching direct current electricity.

(a) Theories about domain-specific learning

In this study the focus has been on validating rather than developing a theory which has centred on inquiry-based science teaching. This has been firmly embedded within the learning theory of social constructivism as a means to generate knowledge in co-operation with others (Hyslop-Magison & Strobel, 2008). Dewey's notion of the learner acquiring knowledge through interaction with the environment has been complemented by the Vygotskian theory of learning through significant others.

When students are engaged in inquiry-based science teaching their understanding of concepts could be enhanced by complementing it with traditional direct instruction methods. It has been shown that when students do show a good understanding they are able to articulate and reason better when they explain science phenomena. The skills that they acquired are transferred to different contexts. In this study this was manifested in the evidence of the students' assessment tasks which were written tests as well as transcripts of verbal data. This supports the notion that the conceptual understanding of PSSTs of direct current electricity can be promoted by engaging in inquiry-based science to develop their process skills. There is, however a need to integrate traditional teaching methods, as is evident from this study, to explain electric circuits.

(b) Means of supporting learning

The theory outlined above is quite broad so by looking at the means to support learning one would look closer at the teaching sequences and actual tasks. These are also underpinned by a well-researched theoretical framework in order to maximise the impact in the classroom. Some of the key features are outlined below:

- Students acquire the ability to explain phenomena when there is a focus on big ideas. In this study the big idea is the flow of charges in a conducting wire. These occur at a micro-level but we focus on a model to explain what happen at a macro-level such as observing the brightness of a light bulb.
- Guided-inquiry tasks allow the students to focus on developing the key concepts in the domain such as current, voltage and resistance.

- The tasks are also collaborative in nature which promotes discussion and dialogue in the classroom. This is a key aspect of inquiry-based science.
- The practical tasks allow for the development of the students' basic and integrated process skills. These are linked to multiple representations in the domain.
- Students develop their argumentation skills by designing and presenting a model that incorporates principles of electricity.
- Problem-solving skills are developed from a quantitative and qualitative aspect. Emphasis should be placed on doing this through direct instruction to solve direct current circuits.

This study supports the findings of Cobern, et al. (2010) that when lessons are carefully designed to develop conceptual understanding in a content domain, it does not matter that the approach is inquiry-based or direct. When conducting research in a real classroom environment using DBR the idea is to account for the complexities that exist. Advocating a narrow focus on an inquiry-based teaching approach has been shown to be limiting, and should therefore be complemented by direct instruction approaches.

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ADDENDA

ADDENDUM A

Science Investigation Rubric

Criteria/Score	5	3-4	2	1	0
Question/ Hypothesis	Question or hypothesis has been thoroughly developed. Hypothesis is correctly stated with both variables identified	Question or hypothesis has been sufficiently developed with reasonable relevancy	Question or hypothesis is partially developed with some relevancy	Question or hypothesis has major flaws and limited or no relevancy	No attempt has been made
Score	_	_	_	_	_
	5	3-4	2	1	0
Investigation Design	Investigation is a well-constructed test of the stated question or hypothesis. All of the developmentally appropriate components (materials, controls, procedure, safety) are arranged so that the investigation can be replicated exactly as described	Investigation is a reasonably constructed test. All of the components are reasonably arranged so that the investigation can be replicated.	Investigation is a partially constructed test. Some of the components are missing, making it difficult to replicate.	Test is not relevant to the question or hypothesis. Information is not sufficient to replicate investigation.	No attempt has been made
Score	_	_	_	_	_
	18-20	11-17	6-10	1-5	0
Methods of Data Collection, Recording & Display	Significant data has been collected in the most efficient and appropriate ways. Data is accurately recorded and displayed using the most relevant and organized methods	A reasonable amount of data has been collected in a sufficient manner. Data is recorded and displayed using organized methods.	A minimum amount of data has been collected. Data is recorded and displayed but may lack some organization.	Insufficient data has been collected. Data has not been recorded or displayed in an organized way.	No attempt has been made.
Score	_	_	_	_	_
	9-10	6-8	3-5	1-2	0
Data Analysis: Conclusions, Inferences, & Recommendations	A precise statement of the investigation results relates directly to the question or hypothesis. Clear assumptions have been made from an accurate evaluation of the conclusion. Recommendations are clearly consistent with the findings of the investigation and provide an excellent defence.	A reasonable statement of the results shows a good relationship to the question or hypothesis. Reasonable assumptions have been made from the conclusion. Recommendations are reasonably consistent with the findings of the investigation and provide a good defence.	A statement of the results provides some relationship to the question or hypothesis. Assumptions are minimally supported by the conclusion. Recommendations are inconsistent with the findings and provide a questionable defence.	A statement of the results shows no relationship to the question or hypothesis. Assumptions are not supported by the conclusion. Recommendations show no relationship to the findings and provide a poor defence.	No attempt has been made
Score	_	_	_	_	_

ADDENDUM B

RUBRIC FOR PROJECT MODEL

Assessment Criteria	**Performance level indicators**			
				Mark
	7-10	**3-6**	**0-2**	
Creativity	Materials are creatively portrayed in ways that enhance understanding about the subject matter. Great care was taken in the construction process so that the model is neat and attractive. The student demonstrates a total understanding.	There was an attempt to use materials in a creative way. Construction was careful and accurate for the most part, but 1-2 details could have been refined for a more attractive product. The student demonstrates a proficient understanding.	Construction demonstrated some effort, but 3-4 details could have been refined for a more attractive product. The student demonstrates a basic understanding.	
Accuracy	Project model displays a high level of accuracy in the manner components are connected	Project model displays a moderate level of accuracy in the manner components are connected.	Project model displays an inadequate level of accuracy in the manner components are connected.	
	4-5	**2-3**	**0-1**	
Function	All components function	1 or 2 of the components do not function	3 or more of the components do not function	
	12-15	**6-11**	**0-5**	
Explanation	All scientific principle are comprehensively explained and the student demonstrates excellent understanding	Scientific principles are explained with a degree of inaccuracy and the student demonstrates moderate understanding	Scientific principles are explained with many accuracies and the student demonstrates inadequate understanding	
			Total	**/40**

ADDENDUM C

NS 278 2011 data

Natural Sciences 2011 (11 Male; 52 Female)

Students	**Science investigation 100**	**Electricity project 100**	**Test 100**
1	0	68	14
2	70	98	40
3	78	75	22
4	70	48	26
5	80	45	24
6	68	70	32
7	68	63	38
8	48	85	18
9	85	78	68
10	73	58	62
11	60	70	38
12	45	70	34
13	40	80	22
14	73	78	32
15	40	85	38
16	70	0	36
17	43	58	60
17	93	78	26
19	63	70	16
20	63	70	70

21	63	55	32
22	38	70	28
23	55	53	22
24	95	73	78
25	58	63	44
26	0	45	28
27	85	78	30
28	85	78	46
29	63	55	32
30	40	70	56
31	63	98	48
32	38	85	48
33	63	68	32
34	55	68	58
35	90	78	78
36	40	70	26
37	55	73	16
38	85	73	42
39	53	63	18
40	93	75	52
41	85	78	34
42	35	48	16
43	85	75	46
44	43	58	32
45	75	53	20

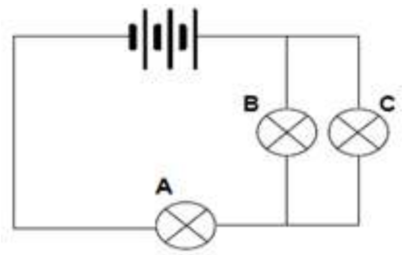
46	63	55	44
47	68	58	56
48	28	70	32
49	75	78	40
50	70	48	42
51	68	58	54
52	88	80	58
53	90	85	32
54	68	85	36
55	100	98	46
56	53	58	38
57	100	78	84
58	60	78	10
59	68	85	62
60	48	58	48
61	78	58	78
62	55	53	18
63	83	78	38
Average %	63.8	69.4	39.6

ADDENDUM D

NATURAL SCIENCES 278
ELECTRICITY TEST
JUNE 2011
QUESTION 1

Choose the answer that best fits the statement. **Only write down the letter of your choice on the answer sheet. Also give a reason for your answer.**

1.1 Three identical bulbs, A, B and C, are connected to a battery. Assume the battery
has negligible internal resistance.



Which ONE of the following combinations correctly represents the brightness of
bulbs A and B, compared to their original brightness, if bulb C is removed?

	New brightness of bulb A	New brightness of bulb B
A	dimmer	brighter
B	brighter	dimmer
C	brighter	brighter
D	dimmer	dimmer

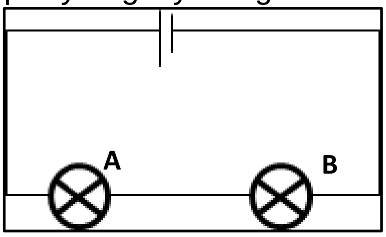
Answer: A

Conceptual trajectory:

This question requires that students engage in qualitative reasoning to explain their answer.

It follows from practical exposure to a scenario in which light bulbs are connected in series and parallel. Observations were based on the relative brightness of the bulbs. It reinforces the idea that a complete circuit still exists when the bulb is unscrewed, but that the parallel branch allowed the current to split. The equivalent resistance of the branch lowered the total resistance of the circuit so that the total current was greater. In series bulb A is dimmer because the current is less, but bulb B is brighter because when it was connected in parallel the split current which it received was less.

1.2 In the circuit shown below the internal resistance of the cell is negligible. Light bulb A glows equally brightly as light bulb B (both are identical).



Which one of the following combinations is the correct representation of the comparison of the **current strength** in each light bulb and the **potential difference** across each light bulb in the circuit?

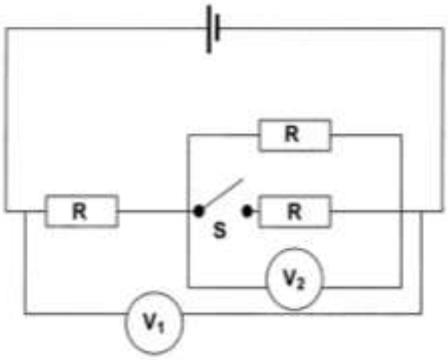
	Current strength	**Potential difference**
A	$I_A < I_B$	$V_A < V_B$
B	$I_A = I_B$	$V_A = V_B$
C	$I_A > I_B$	$V_A = V_B$
D	$I_A = I_B$	$V_A > V_B$

Answer: B

Conceptual trajectory:

This question is relatively straightforward in that it reinforces the fact that the current strength in series is the same throughout the circuit. It also requires that students should intuitively know that identical light bulbs imply the same resistance. An application of Ohm's law (V = I X R) leads to the conclusion that the potential difference is the same across each bulb.

1.3 In the circuit the switch S is open and the internal resistance of the battery is negligible. The resistors R are identical.



How will the readings on the voltmeters change when the switch is closed?

	Voltmeter V_1	**Voltmeter V_2**
A	decreases	decreases
B	stays constant	increases
C	decreases	increases
D	stays constant	decreases

Answer: **D**

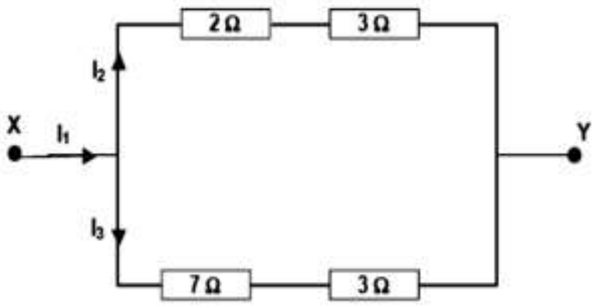
Conceptual trajectory:

This question integrates students' understanding of series and parallel combinations. Voltmeter V_1 is connected across all the circuit elements so the reading remains constant. Voltmeter V_2 is affected by the switch which effectively creates a parallel combination when closed and a series combination when open. When the switch is open the total current is less because the total resistance is greater, but the potential difference across each resistor is the same because the bulbs are identical. When the switch is closed the equivalent resistance of the parallel combination lowers the effective resistance of the circuit so that the total current is increased. The potential difference across the series resistor is greater than when the switch was open. Effectively the reading on V_2 across the parallel combination decreases.

1.4 Which statement/s is/are correct with regard to the circuit?

I	$I_1 = I_2 + I_3$
II	$I_2 = \frac{1}{2} I_3$
III	$V_{XY} = V_{2\Omega + 3\Omega}$

A. I only
B. I and II
C. I and III
D. I, II and III

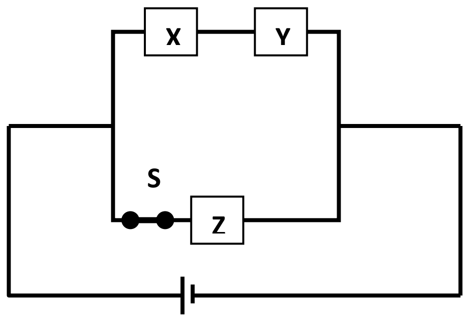


Answer: **C**

Conceptual trajectory:

This question tests students' understanding of parallel combinations. These relate to the current, potential difference and resistance. The total current (I_1) will split in the inverse ratio of the resistance in each branch of the combination. For example, if the resistance is in the ratio 1:2 then the current will be in the ratio 2:1. This is because the potential difference (V) across each branch is the same as across the whole combination. The only statement which is incorrect would be II **($I_2 = \frac{1}{2} I_3$)**. The resistors have also been carefully chosen to allow for easy mental sums should the student wish to do this.

1.5 The three resistors shown in the electrical circuit below are identical. The internal resistance of the battery is negligible.



Switch S is open? How does the current strength in XY compare with the situation when S was closed? Choose the correct statement.

A. The current strength is greater than before.
B. The current strength is the same as before.
C. The current strength is less than before.
D. The current strength is zero.

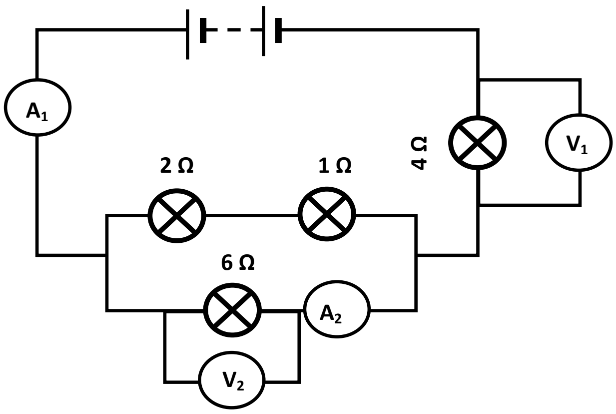
Answer: **B**

Conceptual trajectory:

This question addresses the fact there is still a closed circuit when the switch is open, but that the current in XY is not affected by Z because it is connected to the same energy source. This is an application of I = V / R, where V is the same as when the switch was closed.

QUESTION 2

The battery, ammeter, voltmeter and conducting wires have insignificant resistance. The resistances of the light bulbs are as indicated.



If the reading on V_2 is 6 V, calculate:

2.1 the reading on the ammeter A_2.

2.2 the reading on the ammeter A_1.

2.3 the reading on voltmeter V_1.

2.4 the EMF of the battery.

If the 6 Ω light bulb is disconnected:

2.5 Will the ammeter reading on A_1 **Increase/Decrease/Remain the same** in comparison with 2.2? Explain.

2.6 Will the voltmeter reading on V_1 **Increase/Decrease/Remain the same** in comparison with 2.3? Give a reason for your answer.

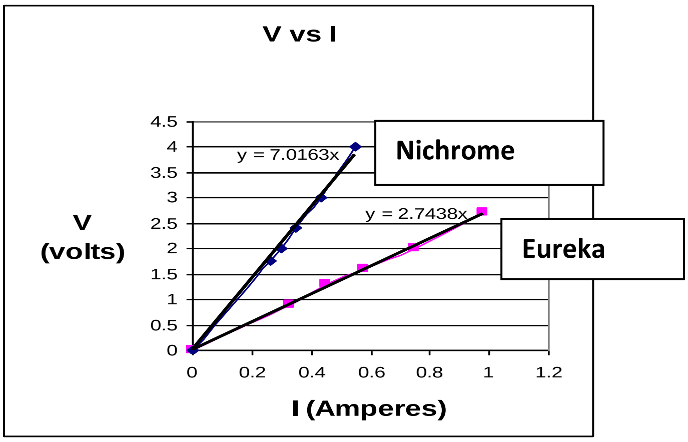
Answers: 1 A; 3 A; 12 V; 18 V; decrease – R more, therefore I is less; decrease - V will decrease since I is less.

Conceptual trajectory:

This electric circuit integrates the students' knowledge of series and parallel combinations and could be considered to be mostly higher-order questions. The first question is a simple application of I = V / R. The determination of the reading on ammeter A_1 requires an understanding of the split current in the parallel branches. This could be done by the ratio method or a calculation based on the fact that the potential difference is the same in each branch. The voltmeter reading on V_1 is simply an application of V = I X R. The sum of all the voltages gives the EMF of the battery. The last two questions further extend the notion of qualitative reasoning. The total resistance increases so that the current decreases
(I = V / R) while the voltage also decreases since the current is less.

<u>QUESTION 3</u>

The relationship between potential difference and current strength (I) for nichrome (0,2 mm) and Eureka (0,2 mm) conductors is investigated. A graph is drawn.

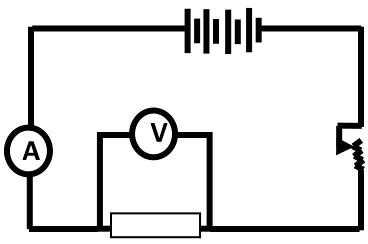


3.1 State a hypothesis for this investigation.
3.2 What two deductions can be made from the graph?

3.3 Draw a circuit diagram to indicate how the components for this investigation should be connected.

Answers:

3.1 Nichrome has a greater resistance than Eureka for the same thickness of the conductor.
3.2 The voltage is directly proportional to the current.
The resistance of Nichrome is greater than Eureka.
3.3

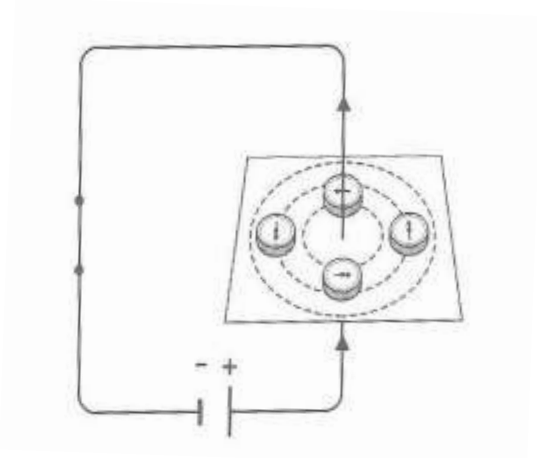


Conceptual trajectory:

Students were engaged in a scientific investigation as part of the experimental work earlier in the module. The aim was to determine the factors that influence the resistance of a conductor. The type of conductor (such as Nichrome) is one factor that was investigated. A graph of voltage against current was plotted from the data that students obtained. The mathematical relationship R = V / I was established from the gradient of the graph. Ohm's law was also formulated in words. These translation activities promoted students' ability to do multimodal representations of a concept. This particular question thus tests their ability to formulate a hypothesis and make deductions from the information given, as well as to provide a diagrammatic representation of the investigation.

QUESTION 4

A group of students observed the following:



4.1 What does the diagram represent?

4.2 Explain the observation by using the right-hand wire rule.

Conceptual trajectory:

This diagram requires that students recognise the magnetic field pattern around a straight current-carrying conductor. They must also be able to predict and explain the pattern by applying the right-hand wire rule. It expands the notion that electric current has a magnetic effect.

ADDENDUM E

Natural Sciences 2012 (12 Male; 48 Female)

Students	Science investigation 100	Electricity project 100	Electricity Test 100
1	56.3	80.0	57.5
2	76.3	80.0	57.5
3	83.8	92.5	70.0
4	71.3	70.0	37.5
5	62.5	90.0	67.5
6	55.0	80.0	25.0
7	50.0	90.0	32.5
8	87.5	82.5	77.5
9	85.0	75.0	25.0
10	86.3	82.5	52.5
11	47.5	80.0	12.5
12	72.5	72.5	45.0
13	80.0	72.5	25.0
14	68.8	90.0	32.5
15	56.3	67.5	25.0
16	40.0	80.0	22.5
17	83.8	80.0	65.0
17	85.0	90.0	72.5
19	78.8	80.0	50.0
20	61.3	75.0	25.0
21	36.3	75.0	32.5
22	66.3	87.5	25.0

23	66.3	62.5	25.0
24	82.5	90.0	35.0
25	90.0	82.5	75.0
26	77.5	72.5	47.5
27	70.0	70.0	25.0
28	73.8	72.5	40.0
29	91.3	87.5	67.5
30	85.0	80.0	72.5
31	56.3	75.0	27.5
32	70.0	87.5	47.5
33	63.8	65.0	35.0
34	83.8	82.5	82.5
35	68.8	65.0	57.5
36	56.3	80.0	25.0
37	52.5	62.5	25.0
38	63.8	80.0	52.5
39	68.8	80.0	30.0
40	76.3	67.5	25.0
41	75.0	80.0	42.5
42	27.5	80.0	32.5
43	58.8	92.5	32.5
44	72.5	72.5	27.5
45	65.0	75.0	57.5
46	41.3	87.5	62.5
47	73.8	80.0	25.0

48	27.5	85.0	25.0
49	31.3	85.0	12.5
50	60.0	80.0	47.5
51	77.5	67.5	27.5
52	91.3	80.0	47.5
53	53.8	92.5	42.5
54	56.3	72.5	25.0
55	36.3	75.0	27.5
56	60.0	92.5	42.5
57	61.3	75.0	25.0
58	81.3	92.5	52.5
59	37.5	75.0	27.5
60	37.5	80.0	40.0
Average %	65.2	79.3	40.9

ADDENDUM F

NS 278 MAY TEST 2012

1.1 **A ✓– Bulb A less current because resistance increases, but bulb B does not get split current✓✓**
1.2 **B✓ - current same in series, pot diff same because bulbs are identical✓✓**
1.3 **D✓ - V_1 reads tot voltage, pot diff across series R is more so V_2 is less ✓✓**
1.4 **C✓ - current splits in parallel, pot diff the same across parallel✓✓**
1.5 **B ✓– V_{xy} same – thus current stays same✓✓**

2.1 **I = V/R✓**
= 6 V/ 6 Ω = 1 A✓✓ (3)

2.2 Current reading will be total.
From parallel: **6 Ω: 3 Ω**
Current 1 A: 2 A (or calculate 6 V/3 Ω = 2A) ✓✓
Tot current = 1 A + 2 A ✓= 3A✓✓

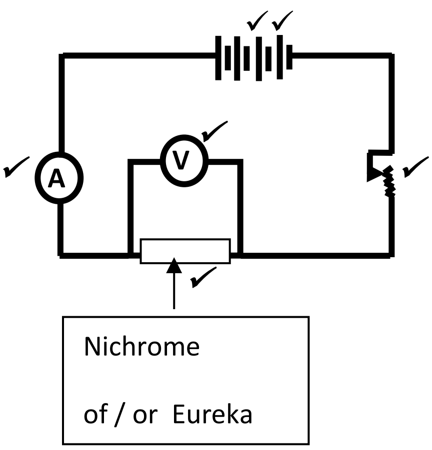
2.3 V = I X R✓
= 3 A X 4 **Ω**✓
= 12 V✓

2.4 V_T (EMF) = 6 V + 12 V✓
= 18 V✓✓

2.5 Decrease✓– total resistance increases✓✓

2.6 Decrease✓– less current so V = I X R will be less✓✓

3.1 Nichrome het 'n groter weerstand as Eureka✓✓ (greater resistance)
OF Nichrome het 'n groter potensiaalverskil as Eureka by dieselfde stroomsterkte
3.2 V direk eweredig aan I ✓✓**(directly proportional)**
Nichrome het 'n groter weerstand as Eureka vir dieselfde deursnee geleier✓✓
3.3



ADDENDUM G

Natural Sciences 278 2013 (6 Male; 41 Female)

	Science investigation 100	**Electricity Project 100**	**Electricity Test 100**
1	75	65	96
2	92.5	65	94
3	92.5	75	100
4	85	65	80
5	80	0	0
6	95	65	80
7	80	75	88
8	90	75	66
9	92.5	67.5	72
10	77.5	75	78
11	55	75	90
12	65	80	74
13	20	67.5	82
14	90	0	44
15	50	67.5	66
16	50	0	0
17	87.5	72.5	68
18	82.5	70	78
19	80	72.5	88
20	87.5	67.5	74
21	87.5	67.5	72
22	95	72.5	86

23	27.5	65	45
24	77.5	67.5	66
25	0	0	88
26	62.5	67.5	34
27	87.5	75	58
28	100	75	86
29	77.5	72.5	88
30	95	75	82
31	82.5	70	54
32	75	70	82
33	0	0	0
34	80	67.5	58
35	45	0	34
36	62.5	65	44
37	85	75	94
38	90	75	84
39	77.5	72.5	82
40	92.5	72.5	94
41	0	67.5	64
42	97.5	75	88
43	97.5	67.5	76
44	75	65	88
45	85	65	88
46	82.5	67.5	72
47	52.5	80	70
Average %	**73.0**	**63.0**	**70.0**

ADDENDUM H

Natural Sciences 278
APRIL Test 2013
50 marks
1 hour

QUESTION 1

The relationship between potential difference and current strength (I) for nichrome (0,2 mm) and Eureka (0,2 mm) conductors is investigated to determine which conductor offers the greatest resistance.

Eureka (0.2 mm)

V (volts)	I (Amperes)
0	0
0.9	0.3
1.2	0.4
1.5	0.5
1.8	0.6

Nichrome (0.2 mm)

V (volts)	I (Amperes)
0	0
2.1	0.3
2.8	0.4
3.5	0.5
4.2	0.6

1.1 Write down a hypothesis for this investigation. (2)

1.2 Draw (on the same set of axes) the relationship for both conductors.

Graph paper is attached. (5)

1.3 Do both conductors comply with Ohm's law? Why? (2)

1.4 Calculate the resistance of each conductor. (5)

1.5 What conclusions can you make from this investigation? (2)

1.6 Draw a circuit diagram to indicate how the apparatus for this investigation should be connected. (4)

[20]

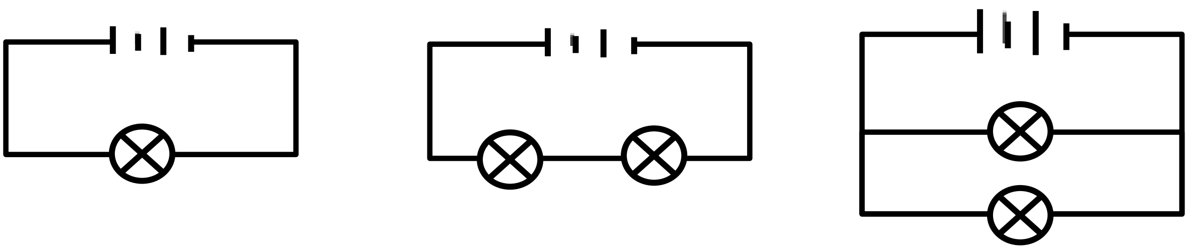
Conceptual trajectory:

This question builds on the scientific investigation that students completed in class. A number of process skills such as hypothesizing, graphing, concluding, etc. are assessed. Implicit in the data is the actual manipulation which requires then the recognition of the dependent and independent variables. More importantly, it also assesses the students' ability to translate data from a table to a graphical representation as well as mathematical when doing the calculation. It further expands on the notion of multimodal representations when students must do a diagrammatic representation of the investigation.

QUESTION 2

Choose the best answer and write down the letter only. Also give a reason for your answer.

2.1 The light bulbs and cells are identical. Which one of the circuits has the lowest resistance?

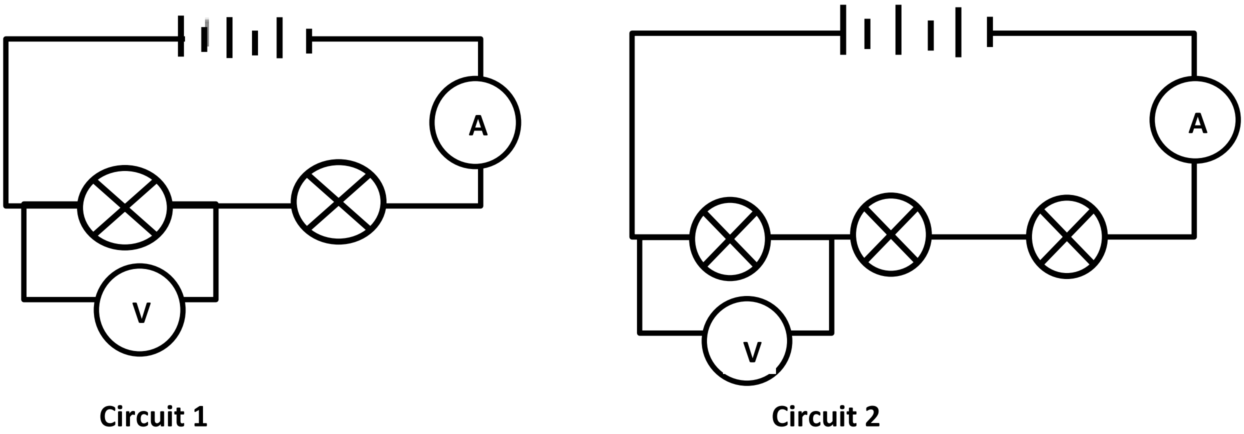


A B C

Conceptual trajectory:

This question reinforces the idea that a parallel combination of resistors lowers the effective resistance in the circuit which is critical to understanding other conceptual questions. These normally elicit explanations such as what will happen if one of the light bulbs is removed. It also builds on the notion of moving away from a formulaic way of doing physics problems.

2.2 The light bulbs and cells are identical.



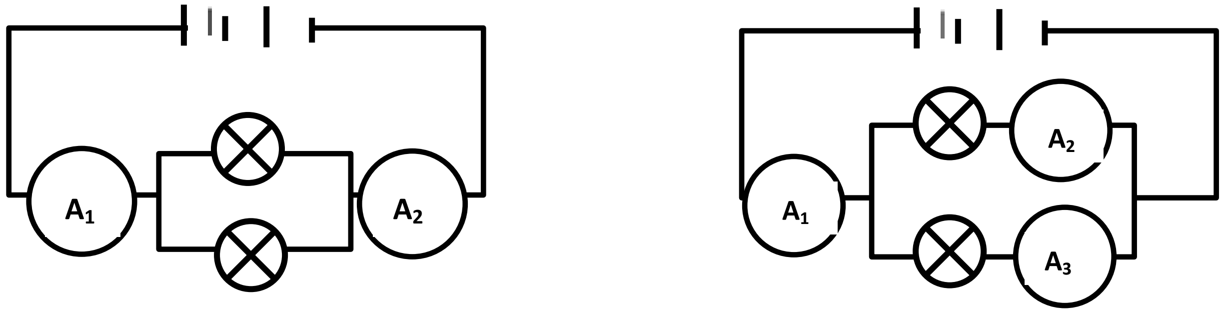
Which one of the following combinations is correct?

A	Circuit 1 has the smallest ammeter reading	Circuit 2 has the smallest voltmeter reading
B	**Circuit 2 has the smallest ammeter reading**	**Circuit 2 has the smallest voltmeter reading**
C	Circuit 1 has the smallest resistance	Circuit 1 has the smallest ammeter reading
D	Circuit 2 has the largest resistance	Circuit 2 has the largest ammeter reading

Conceptual trajectory:

This question simply requires an understanding that an increase in resistance (more light bulbs in series) decreases the current. It also reinforces the concept of inverse proportionality. The students must also understand Ohm's law which relates the current to the potential difference (voltage). Thus, the voltmeter and ammeter are instruments that measure the latter two quantities.

2.3 The light bulbs and cells are identical.



Circuit 1 **Circuit 2**

Which one of the following statements is correct?

A. In circuit 1 A_1 is greater than A_2.

B. In circuit 2 A_3 is greater than A_2.

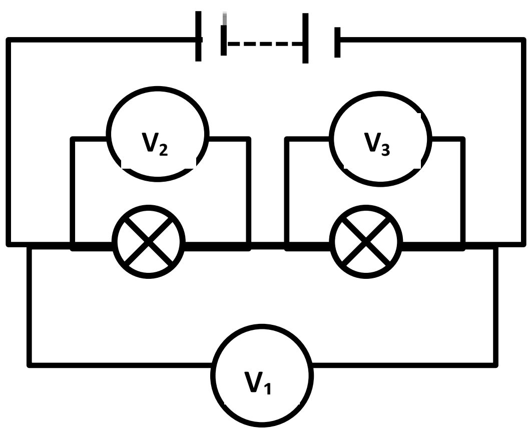
C. In circuit 2 $A_1 = A_2 + A_3$.

D. A_2 in circuit 1 = A_2 in circuit 2.

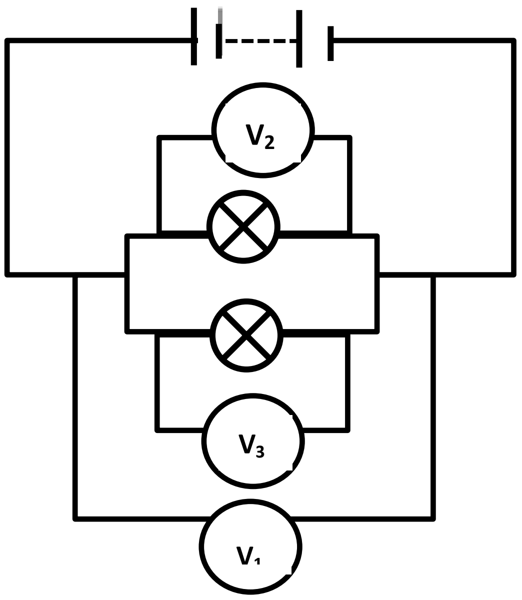
Conceptual trajectory:

This question requires an understanding that in circuit two the ammeters will measure the current in each light bulb. The sum of these two readings will give the total current. The student must therefore have a basic understanding that the current splits in parallel.

2.4 The light bulbs and cells are identical.



Circuit 1



Circuit 2

Which one of the following statements is correct?

A. In circuit 1 $V_1 = V_2 + V_3$.

B. In circuit 2 V_3 is greater than V_2.

C. In circuit 2 $V_1 = V_2 + V_3$.

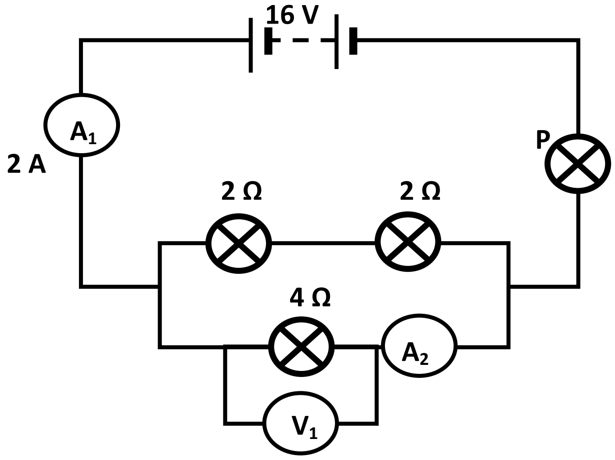
D. V_2 in circuit 1 = V_2 in circuit 2.

Conceptual trajectory:

This question requires that the student must be able to differentiate between series and parallel combinations. In particular, the potential difference is divided in series whereas it is the same across each of the resistors in parallel. Thus, the voltmeter in circuit one measures the total voltage across the two light bulbs in series.

QUESTION 3

The battery, ammeter, voltmeter and conducting wires have insignificant resistance. The resistances of the light bulbs are as indicated.



If the reading on A_1 is 2 A:

3.1 What will the reading on the ammeter A_2 be? Only a reason for your deduction must be given. No calculation will be accepted. (2)

3.2 Use your answer in 3.1 to determine the reading on the voltmeter V_1. (3)

3.3 What is the current strength in light bulb P? Give a reason for your answer. (2)

3.4 What will the potential difference (voltage) across P be? (2)

3.5 Now calculate the resistance of P. (3)

If one of the 2 Ω light bulbs is disconnected:

3.6 Will the ammeter reading on A_1 **Increase/Decrease/Remain the same**? Explain. (3)

3.7 Will the voltmeter reading on V_1 **Increase/Decrease/Remain the same** in comparison with 3.2? Give a reason for your answer. (3)

[18]

Conceptual trajectory:

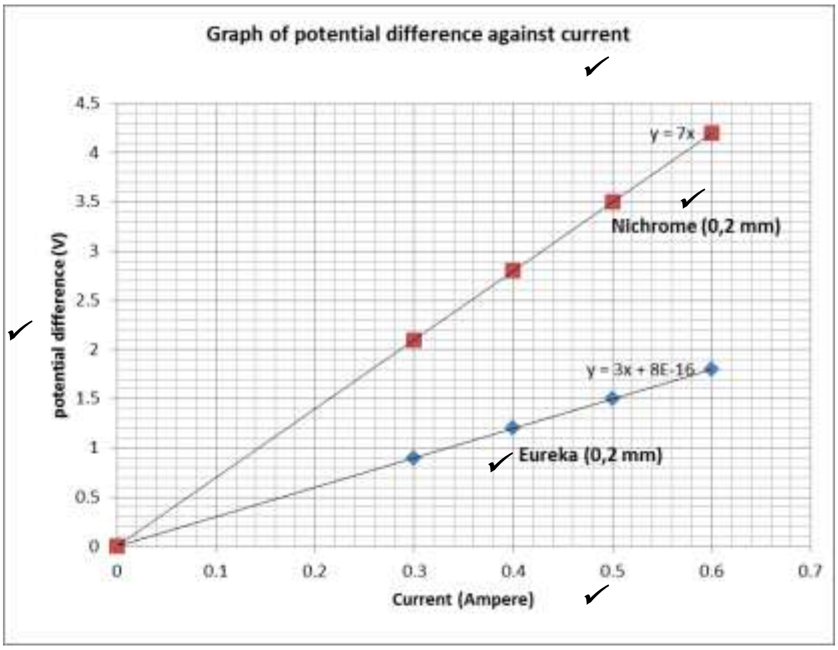
This question embraces series and parallel components. It assesses the students' ability to deduce some answers from the information provided. It gives further opportunities to apply the equation V = I X R, and assesses students' understanding of the basics of electric circuits. Students' reasoning ability is also assessed in the last two questions.

NS 278 TEST 2013

Memo

1.1 Nichrome has a greater resistance than Eureka. ✓✓

1.2



1.3 Yes. V is directly proportional to I. ✓✓

1.4 R = V/I✓

= 1,5 V/ 0,5

= 3 Ω ✓✓

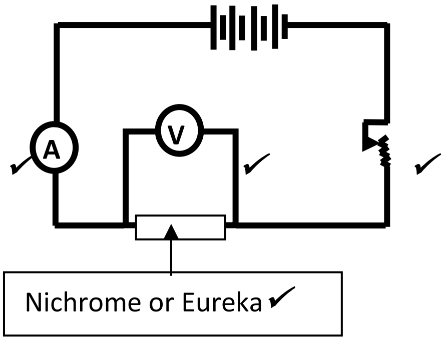
R = V/I

= 3,5 V/ 0,5

= 7 Ω ✓✓

1.5 Nichrome has a greater resistance than Eureka. ✓✓

1.6



2.1 C✓ – parallel combination lowers resistance✓✓

2.2 B✓ – smaller current because of greater resistance, thus V also smaller for same R✓✓

2.3 C✓- current splits so that total current is sum of split current✓✓

2.4 A✓- voltmeter reads total potential difference across two light bulbs. ✓✓

3.1 1 A✓- current splits equally because each arm has 4 Ω✓

3.2 V = I X R✓

= 1 X 4✓

= 4 V✓

3.3 2 A✓ - total current flows through it✓

3.4 V(P) = 16 V – 4 V✓

= 12 V✓

3.5 R = V/I

= 12 V/ 2 A

= 6 Ω ✓✓

3.6 Decrease✓- total resistance increases because no longer have parallel combination.✓✓

3.7 Increase✓- more current passing through in series than when resistor received split current in parallel.✓ ✓

ADDENDUM I

Tables for Fisher's exact analysis of process skills during science investigations

Do the data provide sufficient evidence to indicate that the proportions of students having appropriate science process skills during scientific investigations differ for the three cohorts of students?

From a null hypothesis perspective one would establish whether the two variables are independent. In other words, there is no difference between the science process skills of the three cohorts of students.

In order to answer this question a non-parametric test is applied using categorical data.

1. Hypothesise

	2011	2012	2013
Correct	59	53	39
Weak	3	4	7
moderate	0	3	1
	95.1	88.3	83
	4.9	6.7	14.9
	0	5.0	2.1

```
Observed data: contingency table

       A      B      C

1     59     53     39     151
2      3      4      7      14
3      0      3      1       4

      62     60     47     169

expected: contingency table

        A          B          C

1    55.4       53.6       42.0
2    5.14       4.97       3.89
3    1.47       1.42       1.11
```

The given table has probability 5.4E-04

The sum of the probabilities of "unusual" tables, $p = 0.115$

2. Tabulate

	2011	2012	2013
Correct	32	51	44
Weak	10	1	3
moderate	20	8	0
	80.3	85.0	93.6
	4.9	1.7	6.4
	14.8	13.3	0.0

```
Observed data: contingency table

       A      B      C

1      32     51     44     127
2      10      1      3      14
3      20      8      0      28

       62     60     47     169

expected: contingency table

        A          B          C

1    46.6       45.1       35.3
2    5.14       4.97       3.89
3    10.3       9.94       7.79
```

The given table has probability 5.5E-11
The sum of the probabilities of "unusual" tables finds $p < .001$ i.e., $p = 9.6E-08$

3. Graphing

	2011	2012	2013
Correct	50	45	28
Weak	3	4	13
moderate	9	11	6
	50.8	75.0	59.5
	16.4	6.7	27.7
	32.8	18.3	12.8

```
Observed data: contingency table

       A      B      C

1      50     45     28     123
2       3      4     13      20
3       9     11      6      26

       62     60     47     169
```

```
expected: contingency table

         A           B           C

1     45.1        43.7        34.2
2     7.34        7.10        5.56
3     9.54        9.23        7.23
```

The given table has probability 1.8E-06
The sum of the probabilities of "unusual" tables, $p = 0.007$

4. Analyse & interpret

	2011	2012	2013
Correct	11	17	24
Weak	49	38	17
moderate	2	5	6
	18	28.3	51
	78.7	63.3	36.2
	3.3	8.3	12.8

```
Observed data: contingency table

        A       B       C

1      11      17      24      52
2      49      38      17     104
3       2       5       6      13

       62      60      47     169

expected: contingency table

         A           B           C

1     19.1        18.5        14.5
2     38.2        36.9        28.9
3     4.77        4.62        3.62
```

The given table has probability 4.8E-08
The sum of the probabilities of "unusual" tables finds $p < .001$ i.e., $p = 1.9E-04$

5. Conclude

	2011	2012	2013
Correct	36	47	39
Weak	26	4	6
moderate	0	9	2
	57.4	78.3	83
	42.6	6.7	12.8
	0	15.0	4.2

```
Observed data: contingency table

       A      B      C

1     36     47     39     122
2     26      4      6      36
3      0      9      2      11

      62     60     47     169


expected: contingency table

        A          B          C

1    44.8       43.3       33.9
2    13.2       12.8       10.0
3    4.04       3.91       3.06
```

The given table has probability 2.3E-10
The sum of the probabilities of "unusual" tables finds $p < .001$ i.e., $p = 4.5E\text{-}07$

ADDENDUM J

INFORMED CONSENT FORM

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STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

Title of study: Developing pre-service science teachers' conceptual understanding of electricity

You are asked to participate in a research study conducted by Nazeem Edwards (BSc, HDE (PG Sec), MEd (Science Education) (UCT), from the Curriculum Studies Department at Stellenbosch University.
The results of the study will contribute to a doctoral dissertation (PhD). You were selected as a possible participant in this study because as a prospective science teacher your understanding of electricity will assist in developing an evidence-based practice in science teacher education.

1. PURPOSE OF THE STUDY

To develop pre-service science teachers' conceptual understanding of electricity.

2. PROCEDURES

If you volunteer to participate in this study, I would ask you to do the following things:

- Participate in class during lectures/practical sessions on electricity (6 weeks – 3 periods per week) in the science laboratory.
- Work collaboratively in groups during the practicals/lecture sessions.
- Participate in class discussions & presentations.
- Submit your assignments/practicals/tests for assessment purposes.
- Allow video-recording of practical/lecture sessions.
- Be prepared to be interviewed.

3. POTENTIAL RISKS AND DISCOMFORTS

There are no risks attached to the study other than the usual participation of a student during classroom activities.
No extra time is required except time needed for interviews.

4. POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

Designed-based research looks at the results on an ongoing basis and adapts the study accordingly. As such students benefit in developing their conceptual understanding as things that might not work could be eliminated.
The evidence informs future practice in science teacher education with a potential benefit to learners of these prospective teachers.

5. PAYMENT FOR PARTICIPATION

The participants do not receive any payment for participation in the study.

6. CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law.
Confidentiality will be maintained by **utilizing codes instead of the participants' names. The data collected in the form of hard copies of assessments, will be stored under lock and key in my office at Stellenbosch University. Numeric data and electronic copies of information will be kept on the researcher's computer and access will be granted to personnel involved in the study, namely the supervisor and authorized Stellenbosch University staff.**

Any video-recordings are subject to you reviewing the information. These will be used for the purposes of the study which is educational by nature, and any publication that may emanate will maintain strict confidentiality.

7. PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

8. IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact Nazeem Edwards (0218082291) or Prof Lesley Le Grange (supervisor) (021 8082883).

9. RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

The information above was described to me by Nazeem Edwards in English and I am in command of this language. I was given the opportunity to ask questions and these questions were answered to my satisfaction.

I hereby consent voluntarily to participate in this study/I hereby consent that the subject/participant may participate in this study.] I have been given a copy of this form.

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Signature of Subject Date

SIGNATURE OF INVESTIGATOR

I declare that I explained the information given in this document to

[He/she] was encouraged and given ample time to ask me any questions. This conversation was conducted in [Afrikaans/*English] and no translator was used.