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INVESTIGATING THE LINK BETWEEN TEACHERS' USE OF REPRESENTATIONS AND LEARNERS' CONCEPTUAL UNDERSTANDING OF ELECTRICAL CIRCUITS

by

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Submitted in fulfilment of the requirements for the degree

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UNIVERSITY OF PRETORIA

Supervisor: Dr C Coetzee

October 2024

DECLARATION

"I declare that the dissertation *Investigating the Link Between Teachers' Use of Representations and Learners' Conceptual Understanding of Electrical Circuits*, which I hereby submit for the degree Magister in Science Education at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution."

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The author, whose name appears on the title page of this thesis, has obtained, for the research described in this work, the applicable research ethics approval. The author declares that she has observed the ethical standards required in terms of the University of Pretoria's *Code of Ethics for researchers and the Policy guidelines for responsible research.*

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DEDICATION

This study is dedicated first and foremost to my husband, Eben Harrison, whose unwavering support and commitment have been invaluable throughout all my endeavours – especially this one. Amidst the challenges of emigration and my pregnancy, his encouragement has carried me through this challenging but exciting time in our lives. I never knew unconditional love until I met you.

Then, I dedicate this study to my newborn baby who will probably have arrived by the time this is published. May you be inspired by my absolute love for education and remember that investing in yourself is the best investment you could ever make. I love you so much.

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ABSTRACT

This study explores the link between teachers' incorporation of representations into their conceptual teaching strategies and learners' conceptual understanding of electric circuits. The aim of the research was to thoroughly investigate the link by determining whether learners used and applied the representations taught by teachers while thinking and reasoning about electric circuits. Three in-service teachers, two from Australia and one from South Africa, as well as the learners in their respective classes at the time of the research, agreed to participate in the study. Data was collected by conducting semi-structured interviews with teachers, examining their lesson planning documents, and administering a diagnostic test, which the researcher created specifically for this study. The goal of conducting interviews and examining lessons was to evaluate how well teachers used representations. The purpose of administering the diagnostic test was to evaluate learners' knowledge.

This study has shown that the use of different representations in electric circuits influences learners' knowledge and understanding. Verily, the inadvertent misapplication of such representations can have a significant negative influence on their understanding and reasoning about electric circuits, leading to misconceptions. Furthermore, the study emphasised that learners frequently struggle to effectively distinguish between various concepts, especially those of current and voltage, during the learning process. This highlights the importance of teachers' ongoing reflection and improvement in how they use and present representations during their teaching. The findings of this study could inform both preservice teacher education and in-service professional development, encouraging educators to carefully consider the strengths and weaknesses of the representations. Additionally, this study contributes to the existing body of knowledge on the influence of teachers' pedagogical content knowledge on learner outcomes and supports the concept-specific nature of pedagogical content knowledge.

Keywords: teaching electric circuits, representations, conceptual understanding, misconceptions, pedagogical content knowledge.

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Sincerely,

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LIST OF ABBREVIATIONS

CAPS	Curriculum Assessment Policy Statement
CoRe	Content Representation
cPCK	Collective Pedagogical Content Knowledge
CTS	Conceptual Teaching Strategies
DIRECT	Determining and Interpreting Resistive Electric Circuits Concepts Test
ePCK	Enacted Pedagogical Content Knowledge
RCM	Refined Consensus Model
PCK	Pedagogical Content Knowledge
PhET	Physics Education Technology
pPCK	Personal Pedagogical Content Knowledge

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

CHAPTER 1: GENERAL ORIENTATION

1.1 Introduction and Background

There is an indisputable contention that science is a challenging subject for students worldwide. Millar (1991) attributed science's reputation to four fundamental features: Firstly, science knowledge often fails to offer a satisfactory return for the effort that learners invest in understanding, leaving many learners dissatisfied. Secondly, the process of learning science involves reconstructing meanings, which adds a layer of complexity. Thirdly, the conflicting nature between science as collectively accepted knowledge and science as inquiry creates confusion and, over time, may alienate many learners. Finally, the abstract nature of numerous scientific concepts makes them challenging to comprehend without the use of critical thinking and analysis. Van Gend (2023) reported that fewer South African learners are choosing to pursue challenging science, technology, engineering and mathematics subjects, including physical science, as electives due to the difficulty and perceived lack of real-world value. In South African schools that have been marginalised due to socioeconomic factors, such as rural or poor neighbourhoods, as few as 3% to 10% of Grade 12 learners choose physical science. This is largely attributed to the numerous concepts within physical science topics that require abstract thinking and reasoning (Shirazi, 2017).

Abstract concepts in topics such as electric circuits present many opportunities for learners to develop alternative and incorrect conceptions as they try to understand them. It is not surprising that there have been several global studies exploring alternative ideas about electricity, which have revealed a range of misconceptions across cultural and linguistic boundaries. These misconceptions are held by individuals ranging from children to university lecturers (Burde & Wilhelm, 2020; Coetzee et al., 2022; Moodley & Gaigher, 2019). Numerous scholars have classified and categorised these common misconceptions (Engelhardt & Beichner, 2004; Sencar & Eryilmaz, 2004), while others have used these categories to identify the misconceptions that contemporary learners currently have (Aligo et al., 2021; Moodley & Gaigher, 2019).

In South Africa, several studies have investigated the different ways that both learners and teachers think about concepts in electric circuits (Helm, 1978; Moodley & Gaigher, 2019; Nkopane et al., 2011a). Recent studies have shown that many learners in South African high schools still have misconceptions about concepts regarding electric circuits. In particular, they struggle to differentiate between critical features of electricity, including current and voltage

(Coetzee et al., 2022; Moodley & Gaigher, 2019). The 2019–2021 National Senior Certificate examination diagnostic reports for Grade 12 South Africans include the following suggestion for improving the electric circuit question on the physics paper:

> *Although the principles of series and parallel circuits are taught from Grade 9, the basic principles have to be revised and practiced constantly. The critical features of series and parallel circuits should be reinforced (Department of Basic Education, 2020, 2021, 2022)*

Given that the identical recommendation has appeared in the diagnostic report for three consecutive years, it is evident that electric circuits require further attention as a subject. The quoted text also highlights the notion that sound conceptual teaching can have far-reaching effects on learner performance.

Several factors can affect how learners conceptualise scientific ideas. Among others, these include individual learners' prior knowledge, experiences, cognitive abilities, as well as cultural and societal influences. Additionally, and more importantly for the purpose of this study, the way information is presented may also shape learners' perspectives on scientific ideas. The teaching styles, techniques, and strategies employed by previous and current educators play a significant role in shaping how learners think about concepts in science (Gooding & Metz, 2011; Villarino, 2018). Teachers' choice of instructional methods can either enhance learners' accessibility to and comprehension of content (Pastore, 2024) or potentially contribute to the development of alternative perspectives that might result in misconceptions (Masters, 2018). In topics such as electric circuits where misconceptions are prevalent, it is crucial for teachers to provide quality instruction that identifies, addresses, and corrects any incorrect thinking by learners. This approach helps establish a solid conceptual foundation upon which more advanced and complex electricity ideas can be accurately comprehended.

In the field of science education, teachers are encouraged to promote conceptual understanding of different scientific ideas, processes, and procedures. If *concepts* are described as mental pictures with all the essential features of an object, situation, and idea that allow us to categorise them, then *conceptual knowledge* can be visualised as a connected web of interacting relationships between these different concepts (Hurrell, 2021). Furthermore, where *conceptual knowledge* is the product, *conceptual teaching* is the process that encourages understanding by connecting new information to previously accurately acquired knowledge in a dynamic and continuous manner. Such a process of teaching and learning was described by Shulman in 1986 as the ability of teachers to deliver content to learners in a way that enables them to understand. This is commonly referred to as pedagogical content knowledge (PCK) (Shulman, 1986).

This study uses PCK as the lens through which the conceptual teaching strategies (CTS) of teachers are analysed since there is evidence that teachers' PCK can influence learner performance (Mazibe et al., 2024). Additionally, (Shulman, 1986) introduces representations, such as illustrations, examples, analogies, models, simulations and other resources, as the most frequently used forms of "representing and formulating the subject that makes it comprehensible to others" (p. 9). Instructional representations such as models, analogies, metaphors, and diagrams are commonly used to promote conceptual change among learners studying electric circuits.

The purpose of this study is to identify the representations used by teachers and how they used them when teaching the topic of electric circuits to Grade 9 learners. This is especially important as Grade 9 learners are first introduced to the fundamental ideas in this topic. The study also seeks to determine whether there is a link between the representations used and their effect on learners' conceptual understanding of the concepts being taught. It is hoped that the outcome of this research will contribute to the curriculum development of training programmes for both preservice and in-service teachers.

1.2 Problem Statement

South African learners are underperforming in both mathematics and science. According to the *2019 Trends in International Mathematics and Science Study*, South African learners consistently ranked among the bottom three countries in various assessments conducted (Summer, 2023). A report from Statistics South Africa in 2021 disclosed that inadequate academic performance was the primary cause for 21.2% of Grade 12 learners dropping out of school (Summer, 2023). While several factors contributing to poor learner performance were mentioned, a significant issue is the severe shortage of qualified and experienced educators, coupled with inadequate training and professional development programmes for them (Mmekwa, 2023).

Teaching is a dynamic field, with the needs of learners changing over time. Consequently, instructional methods should be adapted accordingly to ensure that learners' needs are met and they are provided with the best opportunities to succeed (Ramnarain & Hlatswayo, 2018). South Africa is particularly in need of specialist maths, science, and technology teachers who can provide effective teaching and help address the current issue of underperformance amonlearners ("South Africa's Education System in Crisis", 2022). By extension, it is also necessary to identify and analyse teaching strategies that are effective in bringing about conceptual change for contemporary learners.

Of particular focus in this research study is the use of representations within CTS to teach the complex science topic of electric circuits. Since this topic is so abstract, teachers tend to use a wide variety of representations to teach electric circuits concepts since "the learning of complex scientific topics is commonly, even invariably, supported by the use of multiple representations" (Ngwane, 2019, p. 25). The study aims to investigate how teachers can use different representations to improve their learners' understanding of electric circuits concepts and how these can be traced to learners' understanding or misunderstanding.

1.3 Rationale

Research has long explored the misconceptions that students have regarding electricity (Cohen et al., 1983; Helm, 1978; Shipstone, 1984) and has recently revealed their presence in primary school learners (Preston, 2019) and their persistence through high school and even university levels (Villarino, 2018). There is a clear connection between the formation of misconceptions and inadequate conceptual understanding of ideas in abstract topics such as electric circuits in science. Burde and Wilhelm (2020) reported that misconceptions tend to develop as learners are introduced to new concepts and ideas. The role of teachers in preventing the formation of misconceptions and helping learners develop an accurate conceptual understanding of abstract ideas is deeply dependent on how they communicate science to their learners.

Research has been done on different teaching strategies that teachers use to help learners understand abstract concepts better. However, a significant portion of this research pertains to high school learners (aged 16 and above) and tertiary students (college or university attending) (Metioui & Trudel, 2012; Ogegbo et al., 2019). Since misconceptions are often unknowingly created at a time when new concepts are introduced, there is a need to conduct similar research, specifically at this crucial stage. In South Africa, this same pattern is evident in research conducted within the further education and training phase (Gadzikwa, 2018; Ramnarain & Moosa, 2017) and, to some extent, in tertiary education, but it is not as prevalent in the senior phase (Grades 7, 8, and 9). Since learners in South Africa are introduced to the critical features of electric circuits at Grade 9 level (Department of Basic Education, 2011a), it is worth exploring the connection between learner understanding and CTS at this time in the education journey.

This research study focuses specifically on the representations that teachers use to teach the fundamental ideas of electricity and electric circuits to Grade 9 learners. Representations are used as a language of science to effectively communicate and accurately convey abstract scientific ideas and concepts, while also serving as thinking tools to help learners understand (Carolan et al., 2008). As a physical science teacher, I incorporate a wide variety of representations, such as diagrams, moving images, and computer simulations, in my teaching. However, I have observed that not all these techniques lead to a true understanding of concepts, as cautioned by Preston (2019) who noted that using the same representation to teach a particular concept to learners across different age groups does not yield the same outcomes.

While the scientific community has made significant progress in uncovering the various representations embedded in teachers' CTS for complex ideas in electric circuits, there remains an essential need for continuous research on CTS given the dynamic nature of education. It is crucial to identify which strategies are effective and which ones are no longer impactful in facilitating conceptual change in learners. The objective of this research study is to reveal how teachers' use of different representations affects learners' conceptual understanding of electric circuits by revealing the teachers' enacted PCK.

1.4 Concept Clarification

Conceptual teaching strategies: Teaching strategies that are focused on developing an understanding of concepts with less emphasis on knowledge transfer (Mavhunga & Rollnick, 2012).

Electric circuit: The Grade 9 South African curriculum defines an electric circuit as a closed path through which electrons can travel. It consists of a voltage source of negligible internal resistance, fixed in one position, conducting wires of negligible resistance, and at least one output device (resistor) (Johnson, 2020).

Learner: In South Africa, a learner is referred to as a school going child. The school going children that participated in this current research study are referred to as learners.

Representations: As described by Loughran et al. (2012), representations include diagrams, analogies, examples, computer simulations, videos, and demonstrations that present the subject matter in ways that are understandable to learners.

Student: In South Africa, a student is referred to a person attending any tertiary education institution. In other parts of the world, the term student is used interchangeably for any person attending an educational institution, which includes primary, high school and tertiary institutions.

For the current research study, the school going children of Teacher A-C that participated in the study have been referred to as 'learners.' However, the term 'students' that appears part of any literature reference, referring people that attend school or tertiary institutions has remained as is.

Voltage as an energy concept: In this study voltage is conceptualized as a representation of energy, despite its measurement in volts rather than joules, with voltage defined as joules per coulomb. Emphasis is placed on the connection that voltage has to energy conservation and transformation which helps learners to better understand the idea of voltage in electrical circuits.

1.5 Research Questions

The research questions addressed in this study were:*Primary Research Question*

How do teachers use and present representations, as a display of their enacted PCK, to inform Grade 9 learners' understanding of concepts within electric circuits?

Secondary Research Questions

- How do the teachers enact their PCK, as revealed in their lesson planning and reflections during interviews regarding the use of their representations to teach concepts in electric circuits to Grade 9 learners?
- What is Grade 9 learners' understanding of electric circuit concepts after the topic has been taught as revealed in a diagnostic test on electric circuits?
- How can the Grade 9 learners' understanding of the concepts be linked to the representations that the teacher used?

1.6 Summary of Research Design and Methodology

This study adopted a qualitative research methodology aligned with the interpretive paradigm to explore how teachers use various representations when teaching the topic of electric circuits. Using a multiple case study design, the research focused on understanding individual teacher's teaching strategies and their effects on learners' conceptual grasp of electric circuits. Three teachers from South Africa and Australia were purposefully selected to participate in the study because they were teaching Grade 9 Science learners about electric circuits during the research period. The data collection instruments for this study included semi-structured interviews with each of the three teachers, lesson planning documents provided by the teachers themselves, and a diagnostic test designed by the researcher and completed by the learners to assess their conceptual understanding of the topic after it had been taught. The interviews probed teachers' PCK by linking learners' test responses to the specific representations used in instruction. The study aimed to provide an in-depth and holistic understanding of the use of representations in teaching strategies, offering detailed data that focuses on the experiences of teachers and learners. This approach is well suited to a qualitative research strategy.

1.7 Structure of the Dissertation

This section outlines and describes the contents of the six chapters in this dissertation:

Chapter 1: General Orientation

Chapter 1 gives a general overview of the research study. It places the study in context by describing the background supported by the problem statement and rationale, which serves to motivate and direct the study. It includes a section that defines important concepts and listed the research questions that serve as the footprint of the research.

Chapter 2: Literature Review

Chapter 2 provides a summary of the literature consulted on teaching electric circuits in science education, including how teachers' PCK is revealed in the instructional strategies they use to teach this topic. Additionally, it discusses both the conceptual and theoretical framework of the study.

Chapter 3: Research Methodology

Chapter 3 presents the research approach that was adopted for this study. It also evaluates and motivates the use of the research paradigm, methodology, and design, and describes the research site and sample chosen in this study. Thereafter, a detailed outline is provided of the data collection instruments used, as well as the different techniques employed to analyse this data. The chapter then concludes with the quality criteria and ethical considerations.

Chapter 4: Results and Analysis

Chapter 4 presents the results of the analysis obtained from the collected data. These results are presented according to each participant (teacher) and describe in detail what representations they used in their teaching and how they used these representations as a part of their teaching approach. Additionally, the learners' understanding as revealed in the results of the diagnostic test is also discussed in this chapter according to each teacher's use of representations.

Chapter 5: Interpretation and Findings

Chapter 5 presents the summary of the results of the study and interprets these results by discussing some important findings and implications.

Chapter 6: Conclusion

Chapter 6 provides a final summary and answers the primary and secondary research questions. Additionally, the limitations and implications of the study are discussed and recommendations are made for future studies.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The previous chapter introduced the research study and outlined the background, problem statement, and purpose of the study. This chapter provides a literature review that informs the study and guides the analysis and interpretation. Since understanding electric circuits is fundamental in science education and serves as a crucial topic that bridges theoretical knowledge and practical application, this chapter starts by exploring the significance of electric circuits in science curricula. The review initially focuses on the role of electric circuits in the South African education system. This is followed by an examination of its position in the Australian education system. This approach was chosen because the data for this research study was collected from schools in both countries. Thereafter, PCK, the knowledge base unique to teachers, is briefly discussed since teacher knowledge directs the focus of this research. Building on this foundation, the review examines how teachers apply their PCK through various CTS. The review explores documented misconceptions that are prevalent in electric circuits and often guide instructional approaches. Finally, the chapter investigates the use of representations in CTS, especially in the context of electric circuits.

2.2 Electric Circuits as a Topic in Science Education

Electric circuits are commonly included in high school science curricula because of their widespread application in many aspects of everyday life (Burde & Wilhelm, 2020; Kriek & Kotoka, 2019). In educational literature, the topic of electricity and electric circuits taught in schools and universities has been extensively researched and examined. Among others, some of the most widely researched aspects about teaching electric circuits include teachers' knowledge and beliefs about teaching electric circuits (Hermawati, 2022; Moodley & Gaigher, 2019; Webb, 1992); the use of diagnostic tests that provide insight into learners' understanding of electric circuits (Engelhardt & Beichner, 2004; Hesti, 2022); the use of effective teaching strategies to inform learner understanding of electric circuit concepts (Balta, 2015; Brown & Salter, 2010) learners' misconceptions about electric circuits (Helm, 1978; Sencar & Eryilmaz, 2004). Teaching electric circuits is a topic that has been extensively studied due to its abstract nature, which presents significant conceptual challenges and misconceptions for both students and teachers alike.

The abstract nature of electric circuit concepts makes this topic difficult to understand and teach. In a study probing teachers' awareness of and envisaged strategies to address learners' misconceptions about electric circuits, Gaigher (2014) revealed that teachers themselves have a limited conceptual understanding of electric circuits. This is supported by Metioui and Trudel (2012) who found that high school learners, university students, and teachers who hold degrees in physics, still have misconceptions about electric circuits. This topic includes concepts such as current and voltage, which are unseen and abstract. Ultimately, it is up to the student to conceptualise these concepts, and they may be influenced by their individual experiences and interactions with the physical world. This makes it difficult to ensure that the individual paradigms held by students about complex ideas are scientifically sound, which can result in the development of misconceptions (Gooding & Metz, 2011).

2.2.1 Electric Circuits in the South African Curriculum

In the Natural Science and Physical Science syllabus of the Curriculum Assessment Policy Statement (CAPS) curriculum of South Africa, learners are exposed to the concepts of current and voltage at different stages of their educational journey. Learners are first officially introduced to current as the "flow of charges (kinetic energy) through a conductor" (pg. 47) in Grade 8 as they begin investigating the different components of an electric circuit (Department of Basic Education, 2011a). Grade 8 and Grade 9 emphasise the relationship between current and resistance in circuits, including how resistors influence current and factors that affect resistance (Department of Basic Education, 2011a). Electric potential energy is briefly mentioned as an example of potential energy in Grade 7, but only reappears in Grade 10 where it is defined as the work done per unit charge to create voltage. Additionally, in Grade 9, learners are introduced to voltage quantitatively in series circuits as "the total voltage across the battery is the same as the sum of the voltages across each of the resistors" without considering internal resistance (Department of Basic Education, 2011a, p. 73). The chronology of concepts in the Grade 9 curriculum starts with a brief section on electric cells as energy systems, followed by the concept of resistance. The curriculum then covers how the connection of resistors affects voltage and current in series and parallel connections. Unlike current, voltage as an energy concept is not the primary focus in the introductory stage (from Grade 7 to Grade 9) of electric circuits. This discrepancy was also noted by Burde and Wilhelm (2020).

2.2.2 Electric Circuits in the Australian Curriculum

Education in Australia is consistent across the six states, with minor differences in the implementation of the curriculum. Secondary school starts in Grade 7 and proceeds through to Grade 12. It typically includes learners aged 13 to 18. Science is a compulsory subject from Grade 7 through Grade 10, and is taught in two stages: Stage 4 (Grade 7–8) and Stage 5

(Grade 9–10) (Australian Government, 2024). The curriculum outlines concepts that are required for each stage rather than each grade level. Science is divided into biological sciences, chemical science, Earth and space sciences, and physical sciences. Electricity is taught under physical science.

In Stage 4, learners are introduced to energy forms and transformations, including basic electricity and simple circuits. They study electrostatics and energy transfer in circuits, and they also learn how to construct and draw circuit diagrams. At this stage, they are introduced to the concept of current, which refers to the flow of electric charge. They are not yet introduced to voltage, which is similar to the CAPS curriculum in South Africa. As per the New South Wales Syllabus, outcomes in Stage 5 related to electric energy involve identifying the elements of a complete circuit, constructing circuits, drawing circuit diagrams containing multiple components to illustrate the flow of electricity in a complete circuit, and measuring and comparing voltage and current at various points in series and parallel circuits. At this stage, learners may be introduced to Ohm's Law to deepen their understanding, although it is not prerequisite knowledge for subsequent stages (NSW, 2024). In these curriculum outcomes, learners are required to describe voltage, current, and resistance in relation to the energy that is applied, transmitted, and dissipated. Additionally, the outcomes place significant emphasis on practical skills and the establishment of quantitative relationships among variables in circuits. Preston et al. (2020) highlighted the importance of fostering a deep understanding of electric circuits from as early as Grade 6.

2.3 Pedagogical Content Knowledge

2.3.1 The Construct

PCK refers to the exclusive knowledge base of teachers that was first introduced by Shulman in 1986. It is regarded as an academic construct where the content knowledge of teachers (what should be taught) and pedagogy (how it should be taught) meet and combine to form a knowledge base that teachers use to make subject matter accessible to students (Shing et al., 2018). Over time, scholars have modelled the construct differently to understand all that it entails.

According to Grossman (1990), PCK has four central components namely: (1) understanding the purpose of teaching, including knowledge and beliefs about what should be taught at different grade levels; (2) having knowledge about the students, including their beliefs, perspectives, understanding, as well as their misunderstanding of specific topics in subject matter; (3) having knowledge about curriculum components, its progression and the materials required to teach content within the curriculum; and (4) having knowledge about teaching approaches, methods and representations for specific topics included in the curriculum.

Thereafter, Veal and MaKinster (1999) categorised the construct into three hierarchical levels: (1) general PCK (what all teachers know about teaching); (2) domain-specific PCK (what all science teachers know about, for example, physics); (3) and topic-specific PCK (what all physics teachers know about, for example, electric circuits).

In the same year, Gess-Newsome (1999) developed two models to explain the origin and development of PCK: (1) the integrative model views PCK as the connection between educational, disciplinary, and contextual knowledge; and (2) the transformative model describes PCK as the combination of pedagogical, subject matter and context knowledge.

Thereafter, Magnusson et al. (1999) developed one of the most cited models that express PCK as five interconnected components: (1) orientations towards science teaching; (2) knowledge and beliefs about the science curriculum; (3) knowledge and beliefs about students' understanding of specific science topics; (4) knowledge and beliefs about assessment in science; and (5) knowledge and beliefs about instructional strategies for teaching science. Other scholars, including Park and Oliver (2009) and Mavhunga and Rollnick (2012), later refined and developed the components to describe a framework for investigating topic-specific PCK.

The most recent development in describing PCK was presented at the second PCK summit in 2016 (Carlson et al., 2019). In their refined consensus model (RCM), they proposed an approach that "represents the contributions and collective thinking of two dozen international researchers in science teacher education" (p. 77). They identified three realms of PCK, namely collective PCK, personal PCK and enacted PCK. These realms include five components within various knowledge bases used in different settings. The theoretical framework for this current research study was based on two of these realms, namely personal PCK and enacted PCK.

2.3.2 Capturing and Measuring PCK

The PCK construct can be extremely useful in defining the professionalism and competence of an educator, provided it can be captured and measured (Mazibe, Coetzee, et al., 2020; Metioui & Trudel, 2012). However, the recording and interpretation of PCK can be particularly challenging (Lehane & Bertram, 2016) due to the often tacit and personalised construct that is unique to the individual teacher (Barendsen & Henze, 2019). For this reason, various scholars have designed and used alternative methods and instruments. One such acclaimed instrument is the CoRe (Content Representation) tool, which was designed by Loughran et al. (2004). CoRe requires teachers to identify the main ideas to be taught in a topic, which are then analysed using different prompts. Indirect methods for capturing PCK include interviews (Mazibe, Coetzee, et al., 2020; Park & Oliver, 2009); observations (Mazibe, Coetzee, et al., 2020); analysis of lesson plans (Bayram-Jacobs et al., 2019); or hand-written questionnaires.

Chan et al. (2019) developed the grand rubric, an instrument used for constructing other rubrics that evaluate the level at which each component of PCK is displayed based on the RCM of PCK. The rubric includes five components: (1) knowledge of curricular saliency; (2) knowledge of CTS (including representations and analogies); (3) knowledge of students' understanding of science; (4) knowledge of integration between PCK components; and (5) knowledge of pedagogical reasoning. Teachers with low-quality PCK may only display a basic understanding of the five components. On the other hand, teachers with high-quality PCK are able to teach in a way that displays a rich comprehension of most, if not all, of the five components (Mavhunga & Rollnick, 2012). Two of the components in this rubric were used to gauge the quality of PCK among the teachers in this current study.

In recent studies, scholars have used some or all PCK components in their own rubrics to assess the quality of realms of PCK of teachers when teaching a particular topic in science. For example, Mazibe et al. (2023) used three of the five components (curricular saliency, learners' understanding of concepts, and CTS including representations) to assess and quantify the enacted PCK of teachers in big ideas of electrostatics. The current research study occasionally referenced the rubric of Mazibe et al. (2023) to assess the PCK of teachers, focusing on their use of various representations in the CTS employed when teaching electric circuits.

2.4 CTS on the Topic of Electric Circuits

To have an accurate understanding of concepts that are extremely abstract in nature, like those found in electric circuits, Villarino (2018) stressed the importance of having sound conceptual knowledge to bring about conceptual development or conceptual change. Hurrell (2021) defined conceptual knowledge as the knowledge formed by connecting concepts, which are ideas that encompass all the essential features of an object or idea and can be easily associated with related concepts.

Engelhardt and Beichner (2004) conducted a study to assess how well the DIRECT (Determining and Interpreting Resistive Electric Circuit Test) instrument could evaluate students' understanding of direct current circuits. They found that students had difficulty determining a resulting voltage. They relied on procedural knowledge to solve problems instead of connecting related ideas, which is an aspect of conceptual knowledge. Without a strong, conceptual understanding, students' ability to fully grasp and apply abstract thinking becomes limited. This supports the argument made by Burde and Wilhelm (2020) who pointed out that "a(n) introduction to the topic should focus on providing students with a qualitative understanding of circuit behaviour (first)" (p. 3). This means prioritising conceptual knowledge to help learners build a solid foundation moving on to complex procedural thinking and tasks.

Zaitsev (2021) contributed to the thoughts of Hurrell (2021) and Burde and Wilhelm (2020) by describing CTS as a pedagogical approach that focuses on relating concepts rather than presenting isolated bits of information. According to Espera and Pitterson (2019), using CTS is crucial for teaching electric circuits. This is because understanding one concept depends on grasping others, and learners must interrelate ideas to achieve a comprehensive understanding. Additionally, the formation of misconceptions or unscientific ways of thinking can easily occur in the absence of this approach (Espera & Pitterson, 2019).

2.4.1 Misconceptions in Electric Circuits

Misconceptions have frequently been reported in literature as preconceived ideas that do not correlate with scientific thinking (Önder et al., 2017). Gooding and Metz (2011) defined misconceptions as a unique set of misunderstood concepts that are unintentionally developed and often reinforced over time. Scholars have shown that some of these misconceptions exist in the minds of teachers and learners alike (Gaigher, 2014; Moodley & Gaigher, 2019). Sencar and Eryilmaz (2004) categorised electric circuit misconceptions into nine different models:

(1) **Sink model:** Students believe that a single wire connection allows electricity to flow from the power source to the electric component, thus powering it.

(2) **Clashing current model:** Students believe positive electricity flows from the power supply's positive terminal and negative electricity flows from the negative terminal, before meeting at the device to power it.

(3) **Weakening current model:** Students believe that current flows in one direction around a circuit but gradually weakens as it moves through each device that uses up some of the current.

(4) **Shared current model:** Students believe the current is the same at all points in a circuit and that all devices receive equal current, regardless of how devices are connected, but less current returns to the power supply than initially left it.

(5) **Empirical rule model:** Students believe that a bulb will be dimmer the further it is from the power source.

(6) **Local and sequential reasoning model:** Students believe that changes made in circuits affect only that part of the circuit and not the rest of the circuit.

(7) **Short circuit preconception model:** Students believe that wire connections with no devices attached to them can be ignored and do not affect the rest of the circuit.

(8) **Power supply as a constant current source model:** Students believe that a power supply releases a fixed amount of current to every circuit.

(9) **Parallel circuit misconception model:** Students think that adding a parallel path with resistance to a circuit increases the circuit's overall resistance.

Engelhardt and Beichner (2004) added superposition reasoning to the list of misconception models. This is a misconception where students believe that cell configuration does not affect the brightness of bulbs. Many of these misconceptions have been associated with a lack of basic qualitative understanding of simple electric circuit concepts, including current and voltage (Burde & Wilhelm, 2020; Metioui & Trudel, 2012).

Traditionally, voltage has been introduced mathematically to learners without attempting to provide a theoretical qualitative or conceptual explanation of the concept. This is easier to do with concepts such as current or resistance (Burde & Wilhelm, 2020). According to Villarino (2018), the connection between the concept of potential in electrostatics and in electric circuits is often overlooked, which results in current being related to the cause of the electric field rather than voltage. In fact, Burde and Wilhelm (2020) insisted that a "qualitative understanding of voltage as a potential difference should be at the centre of an effective curriculum" (p. 4). Researchers have been continuously exploring teacher knowledge, pedagogy, and different instructional strategies for making abstract concepts such as voltage and current more accessible and easier to understand (Almasri, 2022; Baptista & Martins, 2023; Jaakkola & Veermans, 2020).

2.4.2 Representations as Part of CTS

Shulman (1986) first defined knowledge of representations as part of PCK. This refers to the knowledge of the most valuable forms of representing ideas in topics that are frequently taught. Therefore, the most effective way for a teacher to present subject matter is to formulate it in a way that can be accessed and comprehended by their students. These representations include "the most powerful analogies, illustrations, examples, explanations, and demonstrations" (p. 9). Ngwane (2019) further described representations as multiple ways in which physical concepts or situations can be communicated. Examples of representations used in science teaching are extensive and range from graphs, pictures, and diagrams to analogies, computer simulations, demonstrations, or practical experiments. Shulman (1986) claimed that teachers should have "a veritable armamentarium of alternative forms representations … that originate in the wisdom of practice" (p. 9).

Besides being familiar with representations, teachers should also know how to use them in their CTS in a way that can prevent the formation of misconceptions and/or address misconceptions. Teachers should consider which instructional strategies with representations will result in the conceptual understanding of challenging ideas. Representations, in these instructional strategies, are fundamental to the teaching practices of science educators. Shelley and Kiray (2018) claimed that "without considering science concepts from the vantage point of several different representations, a full understanding of science may not be possible and learning opportunities are reduced" (p. 215).

Science education relies heavily on representations that serve various purposes. Visual elements such as labelled diagrams and graphs are used for illustrating complex relationships and processes that are challenging to articulate (Cook, 2011). The use of three-dimensional models to visualise physical concepts is a popular method used across many scientific disciplines (Balta, 2015). According to Haryadi and Pujiastuti (2020), utilising physics education technology (PhET) simulation software enhances interactive physics learning and proficiency in scientific processes. While the field of science teaching and all its domains use a diverse range of representations, the field of electric circuits stands out with a vast spectrum of such representations.

2.4.3 Representations Used in the Teaching of Electric Circuits

Various representations have been used to teach electric circuits specifically. Several common techniques for teaching electric circuits include the use of analogies, diagrams, digital tools, simulations, and three-dimensional models, such as circuit kits.

Analogies can relate abstract ideas to familiar, everyday phenomena. Research has shown that when applied correctly in educational settings, analogies can be effective in enhancing learning experiences by simplifying complex concepts for students and helping them overcome their misconceptions of these concepts (Chiu & Lin, 2005). In an early study that explored the use of two different analogies to help conceptualise the idea of electricity, Gentner and Gentner (1983) highlighted the importance of choosing the right analogy for explaining complex concepts. They stated that it should be chosen based on the context and learners' needs. For example, while a flowing water model of electricity, which compares electric current to the flow of water through pipes, may help learners to visualise current as a continuous flow of charge, a teeming crowd model, which compares the movement of a crowd through a hallway and focuses on individual particles, like people, instead of a continuous flow, might be more beneficial in complex scenarios where the individual behaviour of electrons matters (Gentner & Gentner, 1983). However, more recently, researchers, including Sullivan-Clarke (2019) and Hungwe et al. (2024), emphasised the double-edge nature of analogies in education, noting that when these mental models are applied incorrectly, they have the potential to create further misunderstanding.

Visual representations are crucial in conveying scientific concepts. They help clarify essential features that may be difficult to explain with words alone, enhancing learners' comprehension and leading to a fuller understanding of the material (Cook, 2011). As with verbal communication, illustrations, graphs and diagrams have to be read correctly to prevent communicating the wrong idea. This is a common occurrence in electric circuits when the circuit's components and connections are not stated accurately. In a study to determine the effect of colouring variables in a circuit diagram on learner understanding, Reisslein et al. (2014) found that students learning with colour-coded circuit variables (blue for voltage, red for current, and black for resistance) scored higher, and experienced lower cognitive load than those with variables in black font. Similarly, Balta (2015) constructed and compared three-dimensional circuit diagrams to demonstrate electric potential and electric potential differences, which improved students' understanding (see Figure 2-1).

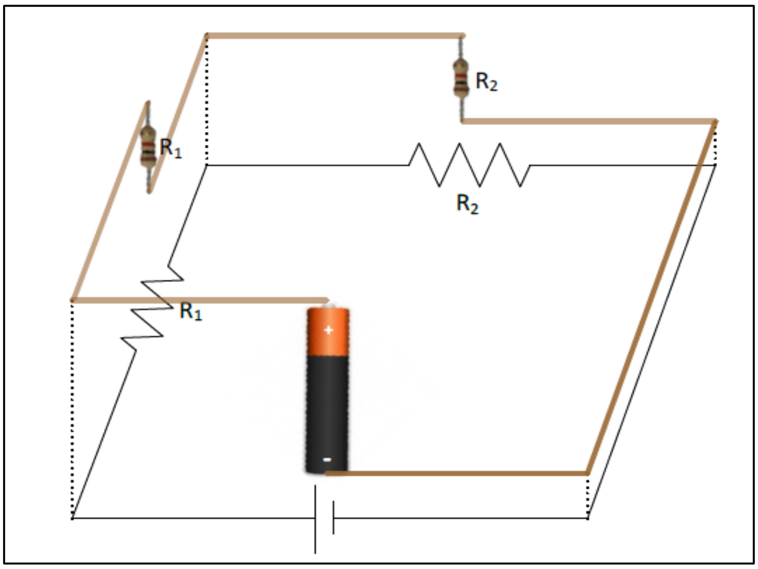


Figure 2-1 – Three-dimensional model with pictures of the circuit elements (Balta, 2015)

Digital tools and simulations simplify and enhance the teaching of electric circuits (Agyei et al., 2024). They provide a relatively risk-free environment for experimenting with concepts that are difficult to replicate in traditional labs, offer immediate feedback on circuit behaviour, and allow students to analyse results, troubleshoot issues, and refine their understanding. There have been many studies on the use and success of simulations in understanding the operations of an electric circuit (Đorić et al., 2021; Gadzikwa, 2018; Ramnarain & Moosa, 2017). In a recent study to examine the effect of problem-based learning using a PhET simulation on students' higher level of thinking, Isbah and Adi (2024) demonstrated that it reduced misconceptions about electric circuit concepts by presenting phenomena that closely resembled real-world scenarios.

However, this does not mean that the use of physical circuit kits is no longer necessary or beneficial. With elementary school students, working with physical circuit boards resulted in a lower cognitive load and more enjoyment of the topic since it provided students with the opportunity to gain practical skills through hands-on experience (Reisslein et al., 2012). Choi and Chang (2004) also highlighted the benefits of using these circuit kits to help learners make the connection between what they learn on paper and how it applies in real life.

2.5 Theoretical Framework

This research study is informed by the RCM of PCK in science education, which was described by Carlson et al. (2019). This model was designed as a comprehensive framework of PCK to conceptualise the idea and provide a lens through which teacher knowledge for teaching can be investigated. The RCM model is presented in Figure 2-2 (Carlson et al., 2019).

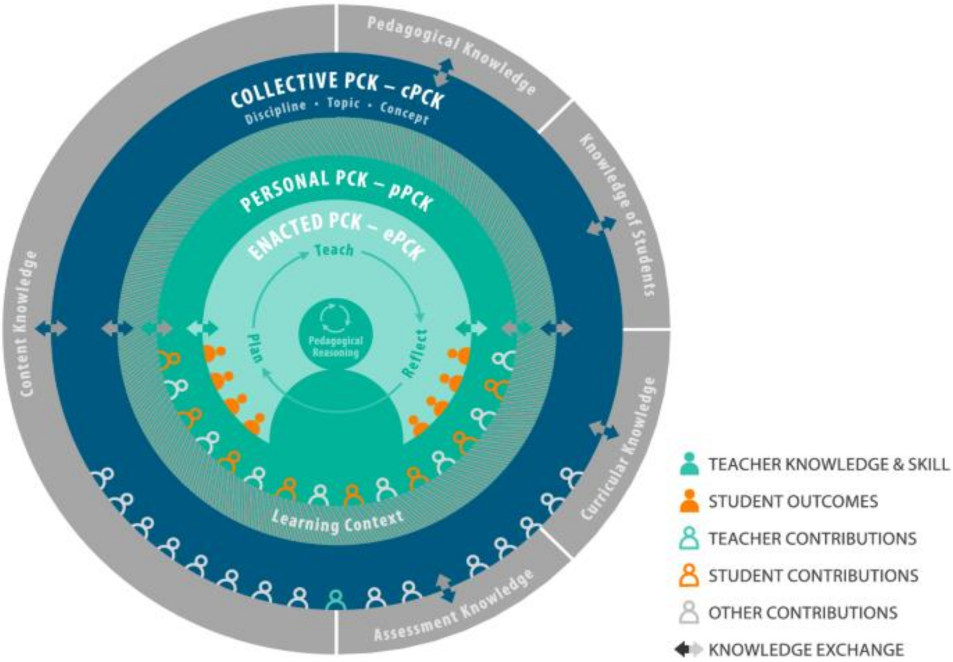


Figure 2-2 – The RCM of PCK (Carlson et al., 2019)

The model separates teacher knowledge into two parts: the first being the general knowledge base (surrounding circle) that includes knowledge about content, assessments, curriculum, students and pedagogy that all teachers possess regardless of the subject taught and that feeds into their PCK. The second part is the PCK, which is apportioned into three realms. The first realm is *collective PCK* (second concentric circle): knowledge on the most effective means of teaching a topic or concept within the domain (like physics) belonging to the profession. The second realm is *personal PCK*: unique knowledge that the individual teacher gains from current and prior teaching experiences. The final realm is *enacted PCK*, which is the knowledge instinctively displayed through planning, teaching, and reflecting in the classroom. It is important to note that enacted PCK is a subset of personal PCK. This implies that the teacher does not enact PCK that they do not have. For example, the way teachers present content during class is based on their training or prior personal teaching experience with that particular part of the syllabus. The RCM forms the theoretical framework for this study since it represents the unique teacher knowledge that is accessed by exploring the representations teachers use and deem most effective when teaching a specific topic, such as electric circuits.

2.6 Conceptual Framework

When the theoretical framework consists of an interpretation of perspectives from acclaimed scholars, the conceptual framework serves as a logical plan of the researcher's specific research process (Kivunja, 2018), which is informed by the theoretical framework. According to Afribury (2021), the conceptual framework guides the research venture by specifying the variables under investigation. The study investigates two components of PCK that have also been used in the grand rubric by Chan et al. (2019). The grand rubric is an assessment tool for the PCK of science teachers. It applies to different forms of PCK as outlined in the RCM, including the individual teachers' personal (pPCK) or enacted PCK (ePCK), along with the collective PCK (cPCK) exhibited by a group of science teachers.

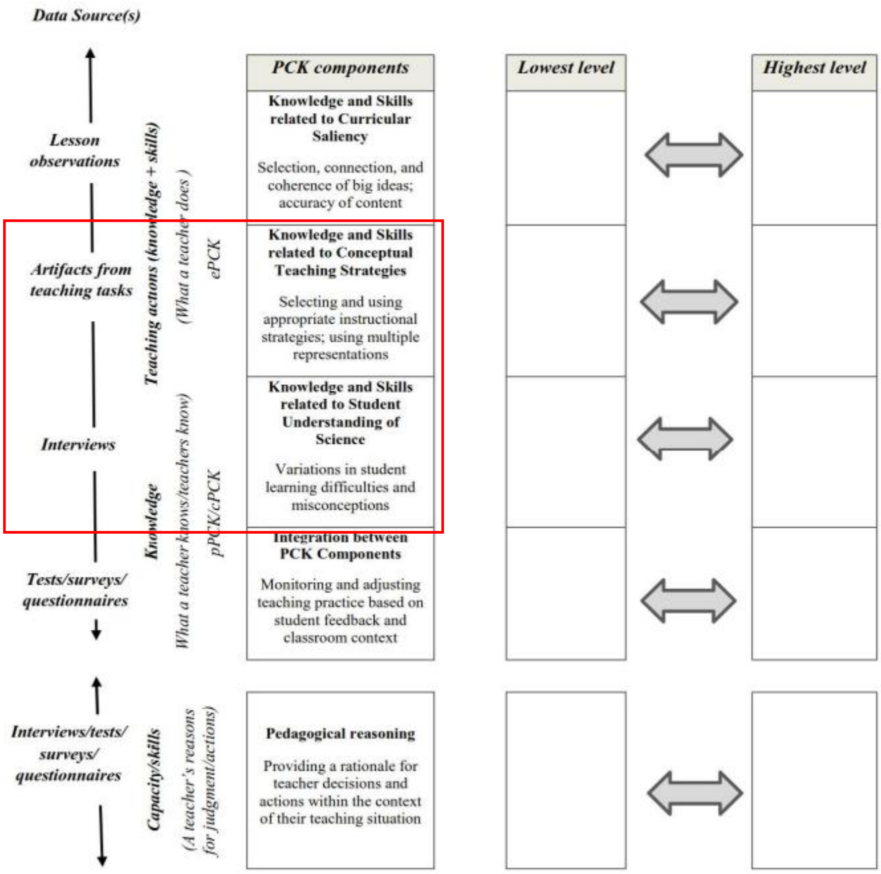


Figure 2-3 – The grand rubric (Chan et al., 2019)

Figure 2-3 shows the layout of the grand rubric and highlights two specific components in red (the second and third listed PCK components from the top) that were selected as variables: (1) knowledge and skills related to the CTS; and (2) knowledge and skills related to learners' understanding of science (Chan et al., 2019). Although two components have been placed strategically within the enacted realm of PCK, they are considered a subset of the personal realm of PCK. Teachers use these components for them to reveal and reflect on their knowledge and skills related to both teaching and learning. The information obtained from the study will be organised into the two components of PCK as suggested in the grand rubric.

To assess the first component, the knowledge and skills related to CTS data will be collected by conducting teacher interviews and reviewing lesson planning documents. In these materials, teachers will demonstrate how they use representations as a part of their CTS in both their teaching and lesson planning. This information will collectively be used to address Research Question 1: “How do the teachers enact their PCK, as revealed in their lesson planning and reflections during interviews regarding the use of their own representations to teach concepts in electric circuits to Grade 9 learners?”

The information regarding the second component, which involves the knowledge and skills related to learners’ understanding of science, will be evaluated based on the answers provided by learners during the diagnostic test and from the interpretation of their explanations by the teachers in the interviews. The answers provided by the learners in the tests will aid to address Research Question 2: “What is the Grade 9 learners’ understanding of electric circuit concepts after the topic has been taught as revealed in a diagnostic test on electric circuits?”.

The explanation that the learners provide to their selected answer as well as any information obtained from the teacher interviews will be used to answer Research Question 3: “How can the Grade 9 learners’ understanding of the concepts be linked to the representations that the teacher used?”

Figure 2-4 illustrates a section of the RCM that visually represents the placement of every PCK component from the grand rubric within the framework, along with the corresponding instruments that will be used to collect data pertaining to each research question.

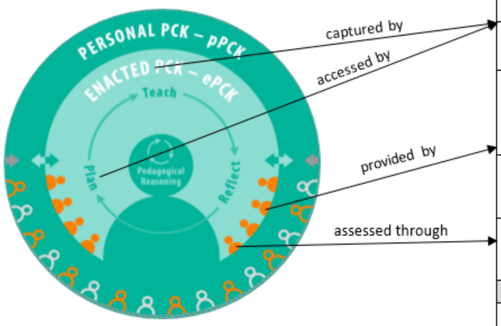
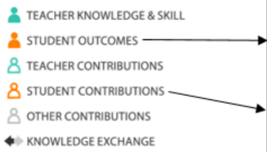
Framework	Instrument	Component of PCK as selected from GR	Secondary Research question addressed
	1. Teacher interviews	Knowledge and skills related to the conceptual teaching strategies	1
	2. Lesson plans		1
	3. Learner tests a. Answers to learners tests	Knowledge and skills related to learner understanding of science	2
	b. Explanation of answers to learners test		3
	4. Learner interviews		3
	Icons in diagram	**Explanation of icons**	
		Enacted PCK influences learners understanding of concepts Personal PCK is influenced by interactions from students (physical work, verbal responses etc.).	

Figure 2-4 – Section of the RCM situated in the personal realm (Adapted from Carlson et al., 2019)

2.7 Conclusion

The topic of electric circuits is conceptually challenging, which means that both learners and teachers need a thorough understanding of the parts involved. This will help ensure learners can fully grasp the topic and that teachers can effectively teach it.

The literature review has highlighted the persistent challenges that learners encounter when studying electric circuits. This has motivated many researchers in the field of science education to investigate and develop effective teaching strategies for electric circuits. While existing literature emphasises the beneficial impact of various teaching methods on learners' comprehension of electric concepts, further investigation is warranted into both the positive and negative influences these teaching methods may exert in the classroom. It includes examining the potential long-term effects of the misuse of representation on students' understanding of electric circuits. Moreover, the review serves as a foundation for exploring correlations between a low science achievement, teachers' PCK, and the use of representations in the context of CTS.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

Grover (2015) defined research approach as the plans and procedures for research that range from "broad assumptions to detailed methods of data collection, analysis and interpretation (p. 1)". In this chapter, the details of the research approach are shared. The chapter begins with these broad assumptions by discussing the research paradigm that frames the study, followed by an explanation of the research methodology. Thereafter, the research site and participant selection process are described, followed by a detailed overview of the data collection methods. The specific instruments used are highlighted and details of how the collected information will be analysed to address the research questions are provided. Finally, the chapter addresses the quality criteria and ethical considerations to ensure that the integrity of the information is maintained.

3.2 Research Paradigm

The study was approached from an interpretive paradigmatic perspective. Saunders and Tosey (2012) defined interpretivism as a philosophy adopted by researchers who are concerned with gathering rich, meaningful insights instead of making conclusions based on patterns or generalisations. Kivunja and Kuyini (2017) as well as Taylor and Medina (2019) acknowledged interpretivism as the paradigm that endeavours to identify with the subject by interpreting information without bias or influence. The interpretive paradigm holds a relativist ontology since it is believed that the situation holds more than one truth, and that this truth or reality is socially constructed – not discovered – which resonates with the study.

The exploratory nature of the study allowed the researcher to gain a coherent understanding of a particular situation without searching for a definite outcome. Specifically, the study investigated the representations used by three science teachers when teaching electric circuits. Qualitative data was collected through semi-structured interviews and lesson plan documents, which were provided by the teachers as additional resources. This allowed the researcher to investigate and interpret multiple truths, which is a distinguishing characteristic of interpretivism.

3.3 Research Methodology

The study followed a qualitative research methodology because it aligned with the attributes of the interpretive paradigm. Jamshed (2014) described the cohesion between the interpretive paradigm and qualitative research methods as one in which the research framework (paradigm) aligns with the type of data collected (qualitative). Interpretivists select participants who each hold their own views about reality, and the researchers gather qualitative data through processes that require deep attentiveness and empathetic understanding (Oancea & Punch, 2014).

This study aimed to provide a comprehensive description of how teachers, who have their own original views of what is and is not effective, use various representations while teaching electric circuits. The best approach is to use methods that gather non-numerical data that can be precisely recorded, thoroughly analysed, and discussed in detail, such as interviews. The study is humanistic and interpretive in nature, which Gill et al. (2008) argued is best researched using qualitative methods. Subsequently, the study is less concerned with ascertaining a general trend in the data and more with being able to copiously understand the use and reason for using specific teaching strategies and representations while teaching electric circuits, as well as with the outcome of the use of these strategies on how learners understand concepts.

Once the topic had been taught, the learners were given a summative task in the form of a diagnostic test, designed and analysed by the researcher, on the specific content that the teacher covered during that period. The researcher and the teacher communicated before the learners completed the test to ensure that the teacher addressed concepts that appeared in the diagnostic test. This summative task included a multiple-choice test that also required learners to provide brief explanations for some of their choices. The outcome of the test, which included the learners' explanations for their answer selection, was made available to the teachers before and during the interview. The researcher used the test results as a basis for discussion during the interview to guide the respective teachers to identify and discuss variations, difficulties, and misconceptions that the learners had presented. Simultaneously, teachers were probed to connect certain learner responses to specific representations they used to teach a particular concept. As teachers described how they taught the topic, including their enactment of PCK, they also provided insight into their personal PCK by interpreting their learners' thought processes when presented with different representations or CTS used. The teachers gave permission for the interviews to be recorded.

3.4 Research Design

In line with the interpretivist paradigm, the study adopted a multiple case study research design. Hunziker and Blankenagel (2024) describe a multiple case study design as a research method focused on analysing data from two or more distinct cases that share characteristics have key differences, enabling deeper comparisons and a broader understanding of a phenomena. Ponelis (2015) justified the use of case studies in an interpretivism paradigm by claiming that:

> *The emerging nature of research in small enterprises is best suited to an interpretive qualitative approach that can yield a rich understanding of key issues by minimizing the distance between the researcher and the (participant) … to develop practical and theoretical understanding and generate new and alternative theories and concepts (p. 538).*

The multiple case study research design was the most suitable for this study since the researcher was specific about the characteristics that the participants had to have and personally selected the teachers under study. As part of this research strategy, the researcher regarded each teacher as a case and followed the five-step research approach seen in Figure 3-1 for each individual case.

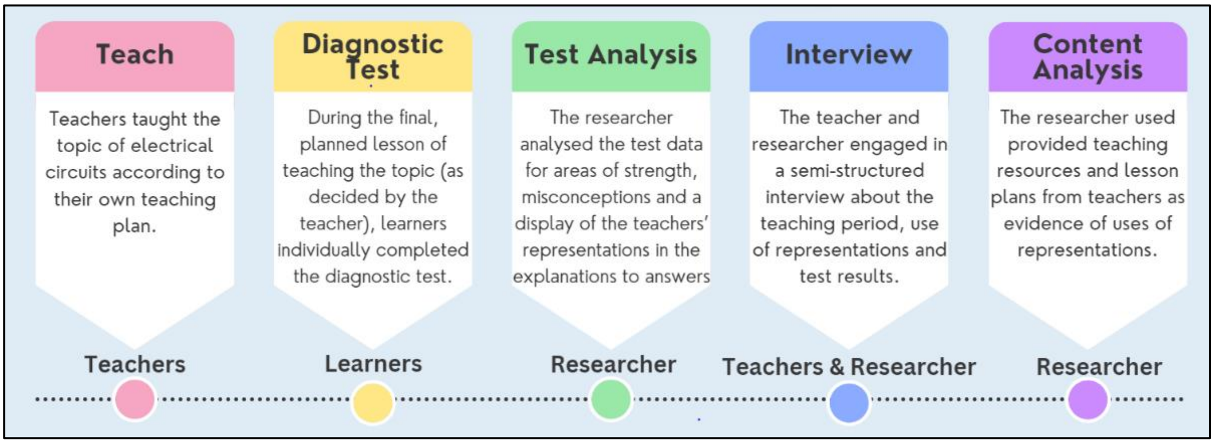


Figure 3-1 – The five-step research process for each teacher

Firstly, teachers taught the topic of electric circuits as planned. The researcher neither attended nor observed these lessons. Secondly, as a means of concluding the topic, learners completed the diagnostic test. Thirdly, once all the learners had completed the test, the researcher analysed the results. Fourthly, the test results together with the CTS employed by the teachers were discussed in depth during a semi-structured interview. Finally, the researcher used and analysed the data collected from the interviews and resources provided by the teachers. The aim was to find a link between the representations used by the teachers (Step 1) during teaching time and the learners' understanding of the concepts (Step 4) that were taught with the use of such representations.

3.5 Selection of Research Site and Participants

McCombes (2023) emphasised how non-probability sampling techniques are mostly used in qualitative research. Among others, these include convenience sampling and purposive sampling; both of which were used within this study. Convenience sampling is often used to select a sample that is most accessible to the researcher at the time (McCombes, 2023). Just before data could be collected, the researcher emigrated to Australia. As a result, the teachers and learners who participated in the study were chosen from schools in South Africa and Australia that were accessible to the researcher during the period of data collection.

Purposive sampling was used to select teachers who would be most useful for achieving the research objectives (McCombes, 2022). For this study, it was a requirement that the selected teachers who participated in both South Africa and Australia taught a Grade 9 Science class during the year in which the data was collected for learners. Additionally, learners as participants, had to be in these teachers' Grade 9 Science class. Another important requirement was that the same fundamental ideas of electric circuits were taught to Grade 9 learners in both South Africa and Australia. Teachers were informed of the study's objectives prior to teaching the relevant section but were advised to proceed with their usual teaching methods, ensuring no alterations to their instructional practices to maintain the integrity of the study. The researcher gave the teachers access to the diagnostic test at the commencement of the research study as a means of verifying whether they had covered all the content included in the test. All the teachers confirmed that they had discussed those ideas with their students at some point during their teaching. Although the content in South Africa is taught at different times of the year than in Australia, this difference did not affect the study results.

In this study, one teacher from an independent school in South Africa and two teachers from the same independent school in Australia were selected to participate in the research. The biographical information of the three teachers is summarised in Table 3.1.

Table 3.1 – Participating teacher's biographical information

Name	Location of School	Years of Teaching Experience	Home Language	Language of Teaching and Learning at School
Teacher A	South Africa	10	Afrikaans	English
Teacher B	Australia	6	English	English
Teacher C	Australia	37	English	English

3.6 Data Collection Instruments

Several data collection instruments, such as interviews, a diagnostic test, and resource documents (like PowerPoint presentations, worksheets, and videos provided by the teachers) were employed to gather information from the study participants.

3.6.1 Teacher Interviews

Gill et al. (2008) noted that the purpose of the research interview is to explore the views, experiences, and motivations of individuals regarding specific matters by being able to probe for richer descriptions of answers. In the study, semi-structured interviews were used to examine the teachers' enacted PCK by analysing the various representations used in the CTS of the teachers and endeavouring to establish a connection between some of the learners' diagnostic test results and the representations used by the teachers.

Each of the three teachers were subjected to a semi-structured interview upon the completion of teaching electric circuits (Annexure C). Jamshed (2014) characterised the semi-structured interview as a controlled conversation in which the researcher "is aware of the respondent and, in times of deviating away from the main issue, refocuses the respondent towards the key subject" (p. 87). The researcher conducted an online interview with Teacher A using Google Meet, which was recorded. The interviews with Teacher B and Teacher C took place in person and the audio recorded.

3.6.2 Lesson Planning Documents

Teachers were requested to share the resources used in their instruction of electric circuits, such as lesson planning documents, PowerPoints, and worksheets. Their resources were used as evidence of the representations employed while teaching the topic, including pictures, diagrams, and videos. This provided the starting point for the interview discussion and analysis of the representation as the researcher investigated the personal PCK of the teacher through this planning and reflection of their teaching.

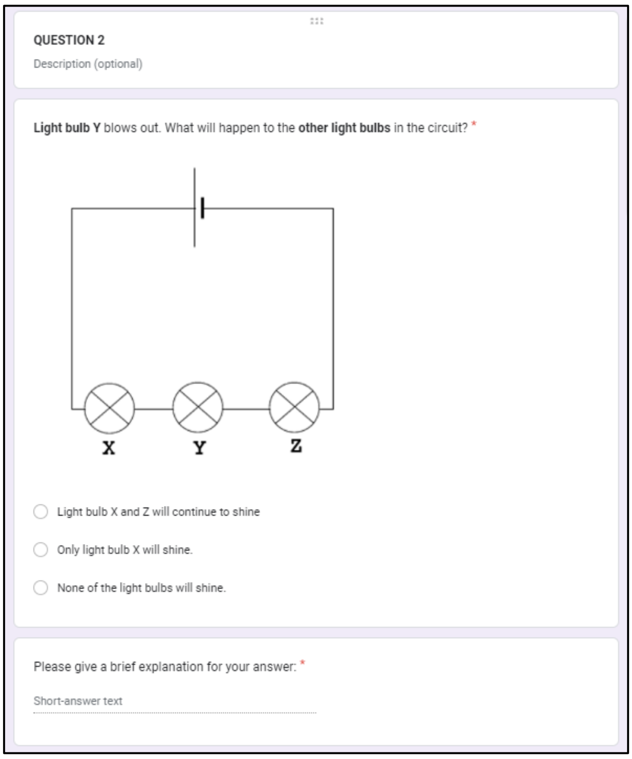
3.6.3 Diagnostic Test

3.6.3.1 Outcomes of the Diagnostic Test

A diagnostic test was used as a tool to assess the conceptual understanding of the learners. The researcher created the instrument (Annexure A) by adapting questions from sources such as the DIRECT test (Engelhardt & Beichner, 2004) and misconception models (Sencar & Eryilmaz, 2004), as well as incorporating ideas based on personal experience or those of other science teachers. Table 3.2 summarises the question sources, the key ideas addressed, how these topics were covered in both the South African and Australian curriculum, and possible misconceptions that may be identified depending on the option selections.

The test was completed electronically via Google Forms, which facilitated convenient data collection and analysis. The test included multiple-choice questions, some of which included common misconceptions about electric circuit concepts as distractors. There were also opportunities for learners to explain their answers for certain questions. Figure 3-2 provides an example of one question on the Google Form.

The questions in the test assessed the learners' knowledge and understanding of electric circuit concepts that do not move beyond Grade 9 level. It is beneficial that the content taught to Grade 9 natural science learners in South Africa closely resembles that which is taught to Grade 9 science learners in Australia.



QUESTION 2
Description (optional)

Light bulb Y blows out. What will happen to the **other light bulbs** in the circuit? *

- Light bulb X and Z will continue to shine
- Only light bulb X will shine.
- None of the light bulbs will shine.

Please give a brief explanation for your answer: *

Short-answer text

Figure 3-2 – Item 2 of the diagnostic test in the Google Form

Table 3.2 – Summary of sources of each question, key ideas addressed, and possible misconceptions identified per question

Question	Source	Key Idea	Topic Covered in CAPS Curriculum (Grade 9 Natural Sciences)	Topic Covered in the Australian Curriculum (Stage 5 Science)	Documented Misconception/s within Option Selection
1	Question 11 DIRECT (Engelhardt and Beichner, 2004).	Origin of charges.	"Cells are a source of electricity" (Department of Basic Education, 2011c, p. 74). "The lighting system in our homes is usually connected in parallel. If one light bulb fuses (filament breaks), the rest of the lights remain on because they are each connected in their own parallel pathway, to the mains circuit" (Department of Basic Education, 2011c, p. 74).	"Describe voltage, current, and resistance in terms of energy applied, carried, and dissipated" (NSW, 2024, p. 53).	• Cells are a source of charge
2	Own teaching experience.	Current flow in series circuits.	"A series circuit provides only one pathway for the current passing through it" (Department of Basic Education, 2011c, p. 49).	"Compare the characteristics and applications of series and parallel electrical circuits" (NSW, 2024, p. 53).	• Sink Model • Local and Sequential Reasoning
3	Combination of own experience and that of other science teachers.	Current flow in series circuits.	"The current is the same everywhere in the circuit" (Department of Basic Education, 2011c, p. 49).	"Compare the characteristics and applications of series and parallel electrical circuits" (NSW, 2024, p. 53).	• Weakening Current Model • Empirical Rule Model
4	Combination of own experience and that of other science teachers. Related to Question 17 in DIRECT (Engelhardt & Beichner, 2004, p. 111).	Current flow in series and parallel circuits.	"The current is the same when measured at any point in a given series circuit (connection)" (Department of Basic Education, 2011c, p. 74). "Resistors in a circuit influence the amount of electric current flowing in that circuit" (Department of Basic Education, 2011c, p. 48). "A parallel circuit provides two or more pathways for the current passing through it" (Department of Basic Education, 2011c, p. 49).	"Compare the characteristics and applications of series and parallel electrical circuits" (NSW, 2024, p. 53).	• Weakening current model • Empirical rule model • Shared current model

Table 3.2 (continued).

5	Com bination of own experience and that of other science teac hers. Related to Question 29 in DIRECT (Engelhardt & Beichner, 2004, p. 114).	Current flow in parallel circuits.	“The total current in the circuit increases with each resistor added in parallel” (Department of Basic Education, 2011c, p. 74).	“Compare the characteristics and applications of series and parallel electrical circuits” (NSW, 2024, p. 53).	• Parallel circuit misconception model • Local and sequential reasoning
6	Question 15 from DIRECT (Engelhardt & Beichner, 2004, p. 111).	Voltage in parallel circuits.	“The voltage is the same across each resistor connected in parallel” (Department of Basic Education, 2011c, p. 74).	“Compare the characteristics and applications of series and parallel electrical circuits” (NSW, 2024, p. 53).	–
7	Own experience.	Relationship between current and voltage in parallel circuits.	“The voltage is the same across each resistor connected in parallel” (Department of Basic Education, 2011c, p. 74). “The total voltage across the battery is the same as the sum of the voltages across each of the resistors” (Department of Basic Education, 2011c, p. 73). “A resistor is a conducting material selected to control the current” (Department of Basic Education, 2011c, p. 73). Relationship between resistance and current.	“Compare the characteristics and applications of series and parallel electrical circuits” (NSW, 2024, p. 53).	–

Table 3.2 (continued).

8	Altered but based on Question 3 in DIRECT (Engelhardt & Beichner, 2004, p. 108).	Cell as a system of electrical energy.	"When cells (of same voltage) are connected in parallel, the voltage across them is the same as for one cell" (Department of Basic Education, 2011c, p. 74). "When cells are connected in series, the total voltage is the sum of the voltages (potential differences) of individual cells" (Department of Basic Education, 2011c, p. 73).	"Compare the characteristics and applications of series and parallel electrical circuits" (NSW, 2024, p. 53).	–
9	Altered but based on Question 19 in DIRECT (Engelhardt & Beichner, 2004, p. 112).	Short circuit understanding.	"A short circuit can occur when an electric current takes the path of lowest resistance" (Department of Basic Education, 2011c, p. 48).	"Compare the characteristics and applications of series and parallel electrical circuits" (NSW, 2024, p. 53).	• Short circuit preconception model
10	Own experience.	Cell as a system of electrical energy.	"A cell is a system in which certain chemical reactions can cause the flow of electricity through an external circuit" (Department of Basic Education, 2011c, p. 73).	"Compare the characteristics and applications of series and parallel electrical circuits" (NSW, 2024, p. 53).	• Sink model
11	Own experience	Connection of voltmeters.	"To measure voltage, a voltmeter must always be connected across (in parallel) a resistor or battery". Suggestions made for practical activities. (Department of Basic Education, 2011c, p. 74).	"Describe voltage, current, and resistance in terms of energy applied, carried, and dissipated" (NSW, 2024).	–

3.6.3.2 The South African Curriculum and the Diagnostic Test

The CAPS document outlines the content to be taught to Grade 9 learners (Department of Basic Education, 2011a):

1. ***Electric cells as energy systems***
    a. *A cell is a system in which certain chemical reactions can cause the flow of electricity through an external circuit.*
    b. *Cells are a source of electricity.*
    c. *A battery is a group of cells that are connected together.*

2. ***Resistance***
    a. *A resistor is a conducting material selected to control the current or to provide useful energy transfer, such as in bulbs, rheostats, motors, light-sensitive diodes, LEDs.*

3. ***Series circuits***
    a. *When cells are connected together in series, the total voltage is the sum of the voltages (potential differences) of individual cells.*
    b. *Resistors can be connected in series in a circuit.*
    c. *The total voltage across the battery is the same as the sum of the voltages across each of the resistors – a resistor with higher resistance will have higher voltage across it – a resistor with lower resistance will have a lower voltage across it.*
    d. *The current is the same when measured at any point in a given series circuit.*
    e. *The total current decreases with each resistor added in series to the circuit.*

4. ***Parallel circuits***
    a. *When cells (of same voltage) are connected in parallel, the voltage across them is the same as for one cell.*
    b. *Investigating the effects of connecting more cells in parallel into the circuit [observe the brightness of the light bulbs as more cells are added].*
    c. *Resistors can be connected in parallel in a circuit.*
    d. *The voltage is the same across each resistor connected in parallel.*
    e. *The total current through the battery is the same as the sum of the currents through the resistors.*
    f. *The total current in the circuit increases with each resistor added in parallel.*

g. *The lighting system in our homes is usually connected in parallel. If one light bulb fuses (filament breaks), the rest of the lights remain on because they are each connected in their own parallel pathway, to the mains circuit.*

3.6.3.3 The Australian Curriculum and the Diagnostic Test

According to NSW (2024, p. 53), the following outcome is to be taught to learners in Stage 5 (across Grades 9 and 10): "Scientific understanding of current electricity has resulted in technological developments designed to improve the efficiency in generation and use of electricity".

Learners at that stage need to be able to:

a. *Describe voltage, current, and resistance in terms of energy applied, carried, and dissipated.*
b. *Describe the relationship between voltage, resistance, and current.*
c. *Compare the characteristics and applications of series and parallel electrical circuits.*
d. *Outline recent examples where scientific or technological developments have involved specialist teams from different branches of science, engineering, and technology, e.g. low-emissions electricity generation and reduction in atmospheric pollution*.

As can be seen above, the Australian curriculum outlines significantly fewer and less detailed outcomes for electric circuits than the CAPS document. Consequently, the researcher confirmed with the Australian teachers that the concepts included in the diagnostic test had been taught and that the teachers felt comfortable allowing learners to complete the test. Annexure B contains all the questions from the diagnostic test, along with the correct answers and the dominant misconceptions that may be revealed by each question.

3.7 Data Analysis

A variety of strategies and tools were used to analyse the predominantly qualitative data that was collected. The researcher collected data that reflected each teacher's PCK, the learners' understanding of science, and the relationship between the two.

3.7.1 PCK of Teachers as Revealed in Interviews and Lesson Plans

According to Carlson et al. (2019), a teacher's *personal PCK* consists of the knowledge and skills that they individually possess regarding the teaching of specific topics, whereas *enacted PCK* refers to the type of knowledge and skills that teachers apply while teaching, including the planning and reflection of their teaching. While the study did not comprehensively assess or measure the current state of teachers' enacted PCK, it aimed to gain insights into the quality of different aspects of their PCK through the reflection of their teaching in interviews and their lesson plans. Specifically for this part of the analysis, the researcher aimed to determine a connection between the representations used and the quality of teachers' PCK.

The transcripts of the teacher interviews were best analysed using thematic analysis since this method is mainly used to understand experiences across a data set by analysing the data according to themes that are either actively constructed or predetermined (Kiger & Varpio, 2020). For this study, the themes were identified as the two selected components suggested in the grand rubric for measuring science teachers' PCK, namely (1) knowledge and skills related to the CTS including representations; and (2) knowledge and skills related to learners' understanding of science.

In this part of the analysis, the representations revealed by each teacher were examined to determine precisely how the teacher used and presented them in the classroom. This information was gathered from interview explanations and any resources provided by the teacher. The way in which teachers used and presented the representations to their learners provided insight into the level of each teacher's enacted PCK.

The quality of the teachers' PCK was evaluated from their use of different representations by applying characteristics of components from various researchers' rubrics, including Mazibe et al. (2023) and Mazibe, Coetzee, et al. (2020) who conducted studies on assessing the enacted and personal PCK of teachers in various physics topics.

3.7.2 Results from Diagnostic Test

The learners participating in this study completed the diagnostic test after the teacher had concluded the section on electric circuits. With the aid of Microsoft Excel, each item was analysed by determining how many learners selected each option in the item and what explanations they used to motivate their specific choice. This analysis was used to determine which concepts were well understood by learners and which misconceptions were most prevalent. Thereafter, the learners' explanations of their reasoning for selecting certain options were analysed to evaluate their conceptual understanding of the electric circuits topics taught. Additionally, these explanations were used to determine whether a connection exists between their thinking and the representations that the teachers used to teach the specific concept that the item in the diagnostic test was addressing. In summary, the test analysis focused more on the nature of the answers to provide insight into the learners' understanding than the quantitative outcome of their performance. The two data sets (teacher knowledge and learner knowledge) were compared to determine how the teachers' enacted PCK influenced learners' understanding of concepts in electric circuits – a means of answering the overarching research question.

3.7.3 Relationship Between Diagnostic Test Results and Teacher PCK

Qualitative content analysis was used to investigate the relationship between the diagnostic test results (learner understanding of science) and the effective or ineffective use of representations (PCK regarding the CTS including representations). Williamson et al. (2013) defined qualitative content analysis as a means of classifying and organising content (which is most often text but may also include verbal or visual content) into categories decided by the researcher for the purpose of analysis. The analysis compared teachers' explanations of fundamental concepts to learners' responses in test items designed to assess those same concepts. One category identified whether the representations were effective aids in achieving learners' accurate conceptual understanding, as reflected in diagnostic test results. The other category examined whether incorrect use of the representations or any misunderstandings caused by them were evident in learners' responses in the diagnostic test.

3.8 Quality Criteria

The trustworthiness of a study involves the amount of confidence that the audience has in its findings and determines whether the study is of high quality and worth paying attention to (Connelly, 2016). The trustworthiness of this study was determined by analysing its reliability, dependability, and validity against specific criteria. To ensure that the study is reliable, efforts were made for the data collection process to be consistent:

- **Diagnostic test:** This summative test was completed by the learners after the conclusion of the topic during a timetabled science lesson. The Grade 9 learners from Australia and Grade 9 learners from South Africa completed the test the same week their teacher concluded the section on electric circuits. In Australia, the two classes were as close together as possible since the teachers' final lessons differed based on their teaching plans.

- **Teacher interviews:** Teachers were probed in similar ways for representations that happened to be the same as their colleagues and for learner responses to the test that came up as similar.
- **Interview schedule:** All three teachers were interviewed during the same week in which they completed teaching electric circuits and administered the test to their learners. This timing ensured that the material and teaching events were still fresh in their minds, and it made it easier to recall and reflect on their teaching and their experience with learners during class time.

The dependability of the study relies on the presentation of evidence. The audio recordings of the interviews were transcribed, coded, and categorised into predetermined themes, which included the two selected components of PCK: CTS including representations and learner understanding of science. The transcriptions were made available to the teachers for member checking and feedback. This ensured that the researcher examined the information correctly and from multiple angles to verify the interpretation of the data (Connelly, 2016). If necessary, the teachers were contacted afterward to clarify any details that were not discussed in the interviews. A record of this interaction was kept.

Heale and Twycross (2015) defined validity as the "extent to which a concept is accurately measured" (p. 1). The validity of the data is supported by the design of the study. The validation of the diagnostic test lies in the fact that many of the questions come from or were based on the existing, validated DIRECT test. Since the diagnostic test did not contribute to their formal scores, learners had no reason to cheat. Additionally, each teacher was asked to encourage their learners to complete the test on their own with no help from their peers. The teacher could help in explaining questions and clarifying information from the diagrams.

3.9 Ethical Considerations

Ethical Clearance and Informed Consent

As this study involves the examination of human informants who provide the information to be analysed, it was conducted only after ethical clearance was granted by the University of Pretoria and consent was obtained from the board of directors of the selected independent schools, the teachers involved, and the learners. Additionally, all learners and teachers were made aware of the purpose of the research and were able to withdraw from the research process at any time and for any reason.

Privacy and Confidentiality

To protect the identities of the involved school, teachers, and learners, the names of all participants were not disclosed in any way in the writing of this dissertation and will remain anonymous. All information provided by the participants will be kept securely at the University of Pretoria and will only be used for research.

Do no Harm

This ethical aspect, often termed beneficence, is a philosophy adopted by researchers that involves the moral obligation to ensure that no harm comes to the research participant while attempting to maximise the benefits of the research task (Beauchamp, 2008). The anonymous nature of the school, teachers, and learners in the study ensures that they will be protected throughout the research project.

3.10 Conclusion

This chapter described the strategies that were implemented to analyse and generate data as part of the research approach. The interpretive paradigm guided the conduct of the study and determined the research methodology as qualitative in nature based on the type of data to be collected. The research design, structured as a multiple case study, was explained, including the instruments used for data collection, namely interviews, lesson planning documents, and the diagnostic test. Furthermore, the chapter emphasised the importance of maintaining quality and addressing ethical considerations. The next chapter will present and discuss the results collected from all three teachers.

CHAPTER 4: RESULTS AND ANALYSIS

4.1 Introduction

This chapter outlines the results of the study, which are presented according to the responses of the three teachers who were interviewed. Using the information obtained from the interviews, diagnostic test, and additional resources provided by the teachers, each representation, as a part of the CTS that the teachers used to teach concepts on this topic, was examined and analysed. This analysis was based on the two components of PCK as mentioned in the conceptual framework, namely teachers' knowledge of CTS and learners' understanding of science.

Research Questions

The primary research question for this study is: "How do teachers use and present representations, as a display of their enacted PCK, to inform Grade 9 learners' understanding of concepts within electric circuits?". To address this accurately, three secondary research questions were formulated:

- How do the teachers enact their PCK, as revealed in their lesson planning and reflections during interviews regarding the use of representations to teach concepts in electric circuits to Grade 9 learners?
- What is the Grade 9 learners' understanding of electric circuit concepts after the topic has been taught as revealed in a diagnostic test on electric circuits?
- How can the Grade 9 learner's understanding of the concepts be linked to the representations that the teacher used?

Collectively, these questions guided the exploration of the dynamics between teachers' knowledge of pedagogical strategies and learners' understanding in the context of electric circuit education.

Data Sources

The data for this study was obtained from three primary sources. The first data source was the teachers' feedback in the interview regarding their instructional methods, which addressed the first research question, and their perceptions of how their learners understood the content, which addressed the second research question. The second data source was the lesson plans provided by the teachers on electric circuits, which addressed the first research question. The third data source was the answers as well as the explanations of the answers provided by the learners in the diagnostic test, which addressed the second and third research questions. In this analysis, information from the interviews, lesson plans, and learner responses was extracted, analysed, and organised based on the two key components outlined in the conceptual framework.

Components for Analysis of Teachers' PCK

The first component is the teachers' *knowledge about CTS* with a specific focus on representations. In the context of this study, a representation refers to any visual, symbolic, or tangible mean, method or phenomenon through which teachers present concepts to their learners. Teachers use various types of representations, including models, simulations, diagrams, and analogies, among others, to facilitate learning and help convey abstract ideas and complex content in a more accessible and understandable manner. The ways in which these representations were used in this study originate from the teacher interviews and the lesson planning they provided. The interpretation of this information provided insight into teachers' PCK and their pedagogical strategies in delivering content about electric circuits to learners.

The second component is the *knowledge of learner understanding*, including knowledge of possible misconceptions in the topic. In this study, the conceptual knowledge of the learners was specifically investigated, which refers to their ability to grasp fundamental ideas and apply new knowledge. The source of the teachers' knowledge about learner understanding of the topic was the teachers' interviews. During these interviews, the teachers reflected on their perceptions of the ability of their learners to comprehend the concepts, as well as the feedback they received during teaching. Additionally, the learners' responses to the questions in the diagnostic test were analysed, with a particular emphasis on the explanations for their chosen answers as this provided a more detailed insight into their thinking and reasoning. The analysis of these explanations has not only provided insight into how and what learners do and do not understand in electric circuit concepts, but has also revealed the extent to which learners rely or reflect on the class-taught representations while conveying their understanding of these concepts.

Analysis Strategy

The data collected from each of the three teachers was analysed and is presented separately. For each of the teachers, the analysis was conducted and aligned with their respective representations. First, the data from the teacher interviews and lesson planning was examined to describe how the teacher used a representation, as part of their *conceptual teaching strategy*, to teach a specific concept related to electric circuits. In the second part of the analysis, the teacher's reflections of *learner knowledge and understanding* revealed in the interview and the learners' explanations for their answer selections in the diagnostic test were used to assess their learners' knowledge of the specific concepts that the teacher taught using the representation. The third part of the analysis used the same data sources to find evidence of how learners may have used this specific representation to assist them in explaining their understanding of a particular concept in the diagnostic test. This final part is essentially an investigation of whether there is a relationship between the representations used by teachers during teaching and how learners used this to formulate their responses to related questions in the diagnostic test. The findings are presented under the headings of the two components: *Knowledge of CTS* and *Knowledge of Learner Understanding of Science.*

4.2 Results of Teacher A

Teacher Description

Teacher A teaches at a private school in Pretoria, South Africa. She has been teaching science for just over 10 years, and she teaches it in her second language, with her first language being Afrikaans. Teacher A taught the topic of electric circuits during the final two weeks of Term 4 of 2023, before the commencement of the yearly final examination. Among other classes, Teacher A taught a class of 25 Grade 9 learners in this co-educational high school. Together with the interview, Teacher A provided three additional resources for analysis: a PowerPoint presentation that supported the presentation of content and sequence of her teaching; a synopsis created for her learners consisting of what she refers to as "rules of circuit analysis"; and a recorded video in which she discusses examples issued as homework to learners during the teaching period.

What follows is the three-part analysis for each significant representation that Teacher A used in her teaching of electric circuits. These three parts, which have been discussed in the conceptual framework, are presented under the two components of teacher PCK and include knowledge of:

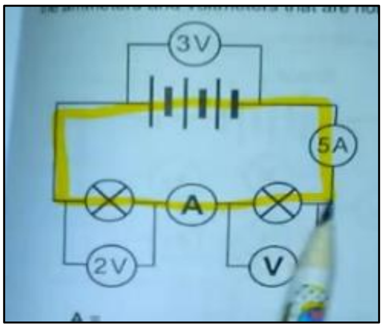
- **Conceptual teaching strategies**
    - What the representation is and how the teacher used it in class.
- **Learner understanding of science**
    - Learner knowledge about electric circuits.
    - Whether a connection exists between the CTS used by the teacher and how the learners understand the concept of electric circuits.

4.2.1 Representation 1 – Colour Coding

Conceptual Teaching Strategies

Teacher A uses colour to highlight circuit diagrams in her PowerPoint presentation or examples drawn on the whiteboard from an exercise in her copy of the learner textbook. On a digital platform, she uses a smart pen to trace the routes that electrons take around the circuit. On a physical resource, like her textbook or whiteboard, she uses highlighters or whiteboard markers. Teacher A mainly uses colour coding to help learners visualise the pathways as electrons move through the circuit "to see where the current is together and where it splits".

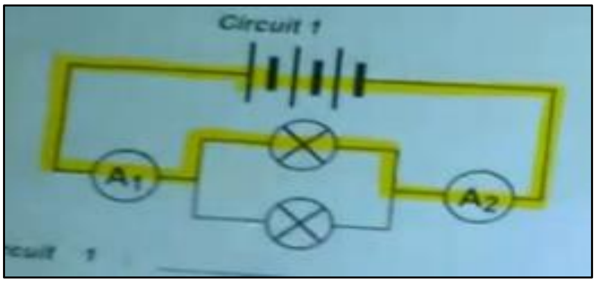
In the first part of her recorded video, Teacher A uses the circuit diagrams provided in the learner textbook to explain concepts. She uses colour coding in the learner textbook as she explains the solutions to questions that were assigned as homework. Figure 4-1 shows a snapshot of a section from the video where Teacher A highlights the path on the circuit diagram and says the following:



Now the reason why I'm colour-coding the pathways is because it shows me where the current is flowing, so where are the charges going … so there's only one pathway here.

Figure 4-1 – Series circuit: Colour coding

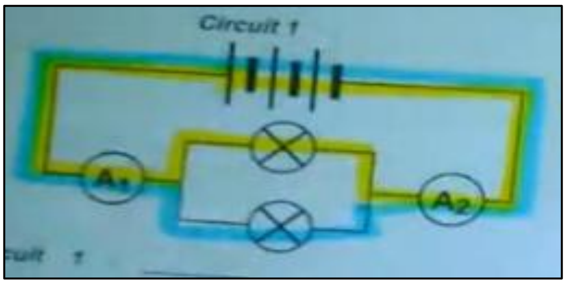
Figure 4-2 shows a moment in the video just before Teacher A discusses the numerical solutions to questions in the learner textbook. She first introduces the circuit layout by highlighting the different paths that the electrons can follow in a parallel circuit and mentions:



Question 16 is a parallel circuit. So now, instead of the charges only having one path on which they are going to move …

Figure 4-2 – Parallel circuit: Colour coding for Route 1

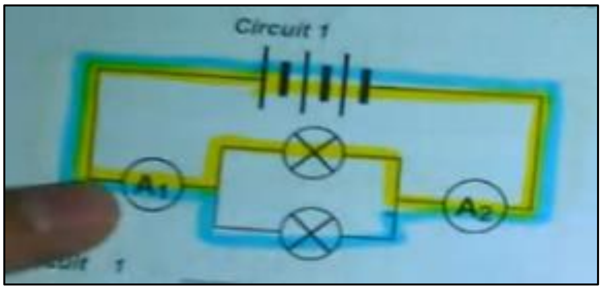
Immediately thereafter, she uses a different colour to reveal another path that the electrons could take and continues (Figure 4-3):



…at some stage the current is going to split. So that's why I'm going to use two colours.

Figure 4-3 – Parallel circuit: Colour coding for Route 2

To teach the concept of current flow at different parts in a parallel circuit, Teacher A uses the same circuit and explains that the current through the ammeter in one part of the series circuit (A_1) is the same as the current through the ammeter in another part of the series circuit (A_2) since there are two colours running through it. Figure 4.4 shows a snapshot of this moment in the video with the corresponding audio:



Here, they want to know what is the relationship between A_1 and A_2. Now if I look at this, A_1 has both of the colours <u>through it; A_2 has both of the colours</u> through it. So, since they have the same amount of colours through it, it means it must be the same size current.

Figure 4-4 – Current flow at different parts of a parallel circuit

Pay attention to the path that Teacher A follows while highlighting the circuit diagrams. Although always referring to the "movement of electrons", she gestures with her hand and aligns the pen with the conventional direction of current. While this might not have caused learners to respond incorrectly to items on the diagnostic test, it does indicate a gap in the teacher's knowledge of learner understanding. Something as simple could potentially cause confusion later on regarding what actually moves in a circuit, be it positive charge or electrons. Since this representation lacked this clarification, her PCK in understanding how learners grasp this concept in science is limited (Mazibe et al., 2023).

Teacher A also uses colour for another, slightly different reason. Teacher A created a document of circuit rules that summarises the different rules and relationships of circuit analysis. In the document, Teacher A used colour to help her learners understand how an equation can mathematically represent what is being displayed in a circuit diagram. Here, she made a special effort to introduce inverse and direct proportionality through means of equations, circuit diagrams, colour, words and examples (as shown in Figure 4-5). Note how the colours of the voltmeters $V_1, V_2,$ and V_3 in the circuit diagram match the colours of the symbols in the equation given below the circuit diagram. She used several such representations throughout the document.

Learner Understanding of Science

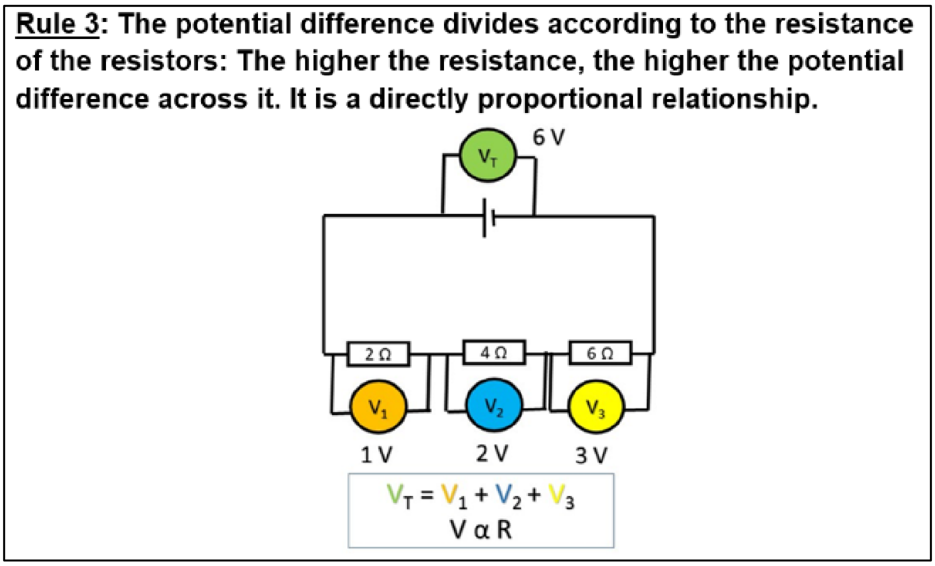


Figure 4-5 – Colour to show how voltmeters in the circuit diagram and symbols in the equation correspond

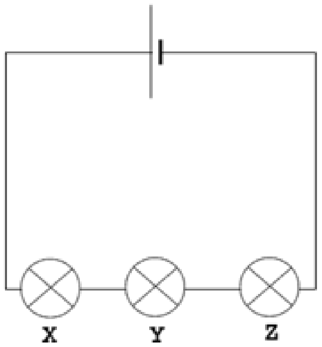
The data that was used to assess the impact of using colour highlighting on learners' understanding of electric circuit concepts was sourced and analysed from their responses to particular diagnostic test items that pertain to current flow in both series and parallel circuits.

In the interview, Teacher A recalled that she knew her learners understood the distribution of current through various circuit connections. While they may not always use the correct scientific terminology when describing what current means, they are able to identify that "this one plus this one gives you that one or, because we colour-coded, this ammeter reading is the same as that one (ammeter) because the same colours are going through it". She also noted that, at the beginning of the topic, her learners demonstrated prior knowledge of current, including its unit of measurement and how to connect ammeters in a circuit.

In Item 2 of the diagnostic test (Figure 4-6), 22 out of 25 learners (88%) selected the correct option (Option C), demonstrating an accurate understanding of open or closed circuits as well as current flow in a series circuit.

Question 2

Light bulb Y blows out. What will happen to the **other light bulbs** in the circuit?



A. Light bulb X and Z will continue to shine.
B. Only light bulb X will shine.
C. None of the light bulbs will shine.

Figure 4-6 – Item 2 of the diagnostic test

In three of their explanations provided below, learners refer to the path that electrons move along in the same way as Teacher A described it with her colour-coding representation:

> *Once the light bulb breaks, there is no path for the current to flow in the circuit, as it is broken.*
>
> *In a series circuit, there is only one pathway for charges to flow. If that pathway is broken no charges can flow (the circuit becomes incomplete).*
>
> *When light bulb Y blows out it creates a breakage in the circuit. The circuit is thus incomplete meaning there cannot be a flow of electric charges in the circuit. It is a series circuit so the one and only pathway for current has been broken.*

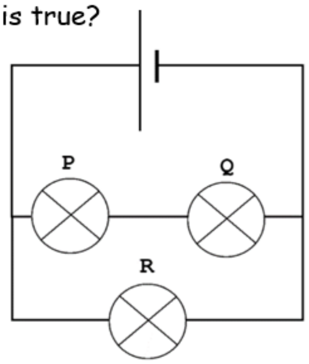
Additionally, the results of Item 4 on the diagnostic test (Figure 4-7) not only demonstrate that Teacher A's learners understand current flow through components connected in series but also understand current flow through components connected in parallel. Out of the 25 learners, 18

(72%) selected the correct answer for Item 4 (option C). Two explanations provided for this selection are included below:

> *The current divides between the branches (based on their resistance) and P and Q get the same current as they have the same resistance.*
>
> *The parallel circuit provides more options for the circuit to move.*

Question 4

In the circuit below, all the light bulbs are identical. Which one of the following statements is true?



A. The current in P is greater than the current in Q.
B. The current in P is greater than the current in R.
C. The current in P is the same as the current in Q.
D. The current in P is the same as in Q and as in R.

Figure 4-7 – Item 4 of the diagnostic test

Moreover, some explanations revealed that many learners could explain how current and resistance are related to each other, with one explanation mentioning the voltage (energy) between those two points as well:

> *The current will remain the same throughout the branch. However, as it [branch with P and Q] has double the resistance, the current will be half of R.*
>
> *P will be the same as Q as they are connected in series. But R on the other hand, will burn much brighter as they both get the same energy but have different levels of resistance.*

4.2.2 Representation 2 – People-Charge Analogy

Conceptual Teaching Strategies

Teacher A found that the topic of voltage or potential difference was difficult for the learners to understand. Every year, when assessing their prior knowledge at the beginning of the teaching course for electric circuits, she recognised that voltage as an energy concept is completely unfamiliar to Grade 9 learners, unlike the idea of current as the movement of electrons through the circuit pathway. To help learners understand voltage as the difference in electrical potential energy that charges have when they are at different points in a circuit, Teacher A uses an analogy. In this analogy, she compares the charges or electrons that move through the wires of a circuit to people moving along on a specific pathway. She explains that the energy that the charges collect from the cell and use to move through the circuit:

> *… is like money. You get money from the cell. Now you look, where are you walking? Where am I going on that coloured line?*

Then, in order for the charges (people) to move through a resistor, they must *spend money*. So, the cell is seen as the place where people *receive money,* and the resistor is the place where people *spend or use their money*. Additionally, she introduces the idea of energy conservation along with the way charges distribute energy throughout the circuit. This money (energy) is received from the cell as charges move through it, and it must be spent or used to go through all of the resistors in the pathway before the charges return to the cell to collect more money (energy). Teacher A repeats this idea often: "Whatever I got, I have to use".

In Teacher A's PowerPoint presentation, she discusses the rules of circuit analysis on slide 42, starting with series circuits and then progressing to parallel circuits. For series circuits, each on a separate slide, she describes four rules. Figure 4-8 displays her rules as they appear as slides in her PowerPoint presentation:

- **Rule 1:** Current strength remains constant.
- **Rule 2:** Resistors split the volts = potential difference dividers – adds up to potential difference across cell.
- **Rule 3:** Resistors divide potential difference – the higher the resistance, the higher the voltmeter reading.
- **Rule 4:** The higher the total resistance, the lower the total current.

Teacher A uses a colour-coding technique to explain Rule 1. While Rule 2 and Rule 3 both relate to voltage, this people-charge analogy is mostly used to explain Rule 2.

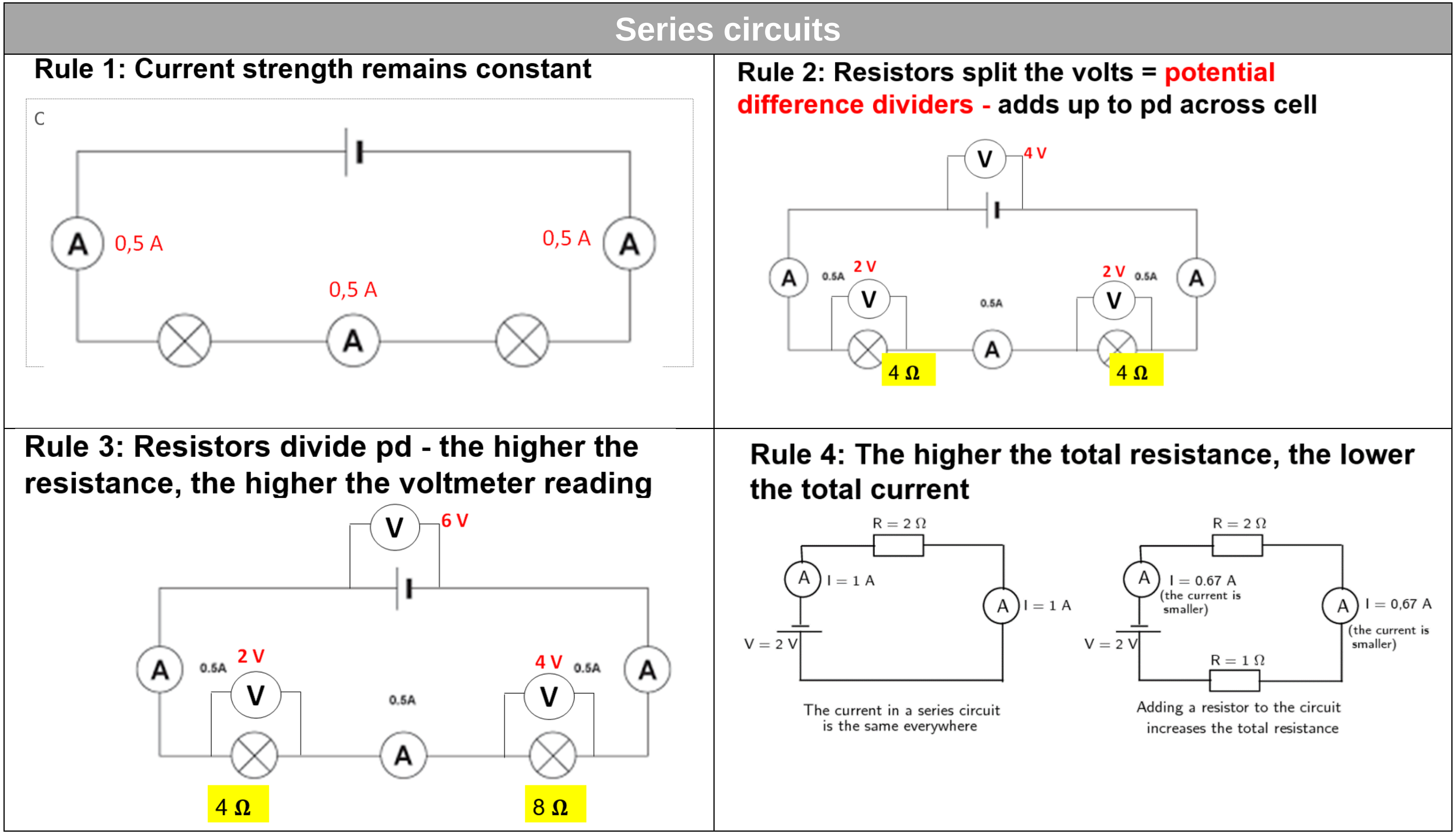
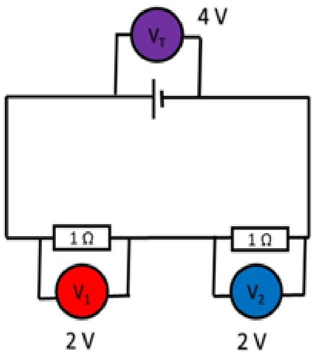


Figure 4-8 – The rules of series circuits used in Teacher A's PowerPoint presentation

In the document of circuit rules that Teacher A gave to her learners as a study resource, these same four rules are presented in the same order. Figure 4-9 shows how Rule 2 was presented to learners in different forms in the circuit rules document made by Teacher A. First using words and full sentences, second with a coloured circuit diagram, and third with a mathematical equation. Since this correlates with the same rule on her PowerPoint presentation, it would have been particularly useful in helping learners recall what was taught in class and to build their conceptual knowledge by presenting the same information in multiple formats.

Rule 2: The potential difference (voltmeter readings) across the resistors in a series circuit adds up to the potential difference across the battery.



$$V_T = V_1 + V_2$$

Figure 4-9 – Rule 2 as presented in the circuit rules document of Teacher A

In this instance, we observe the PCK of the teacher, as she skilfully incorporated three distinct representations within a single resource, assisting her learners in making connections between different ways of communicating ideas. Here, the teacher exhibited quality PCK by using various representations as part of their CTS, allowing learners to confront concepts that are difficult to understand (Mazibe et al., 2023).

We will now examine how Teacher A presents this analogy to her learners as she analyses circuits in the video she made for their independent study.

a) The cell as a money (energy) source

In this analogy, Teacher A explains that the cell is the place where the charges collect energy. This idea is used in conjunction with energy conservation, as the energy that the charges collect from the cell every time that they move through the cell needs to be distributed between all the resistors every time that they move through the circuit. Two circuits have been chosen from the video, one with resistors in series (Figure 4-10) and the other with resistors in parallel (Figure 4-11) to demonstrate her strategy:

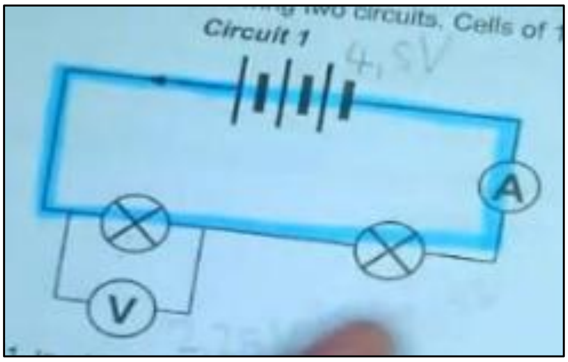


Figure 4-10 – Video extract of resistors in series

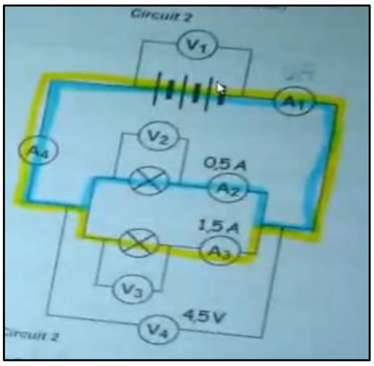


Figure 4-11 – Video extract of resistors in parallel

In your mind, potential difference is the amount of money that I got. So, if one cell is 1.5 (V), then three cells would be 4.5 V. Now, your aim in a circuit is to take that energy and use it to go through your circuit.

*The yellow people for this whole circuit, only went through one resistor. If they used 4.5 V they must have gotten 4.5 V at the start. **Because whatever you have, you have to use** to move through the circuit. If you only have one resistor in your pathway then what you got was used over there.*

b) Resistors as places where money is used or spent

Figure 4-12, Figure 4-13 and Figure 4-14 are snapshots of moments in the video where Teacher A used the people-charge analogy to explain how resistors are places where money needs to be used or spent.

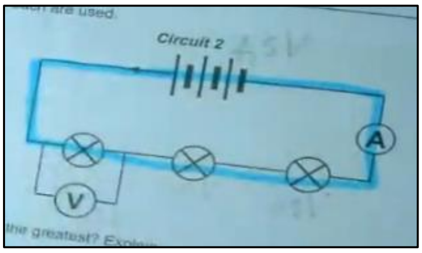


Figure 4-12 – Resistors as places to pay money

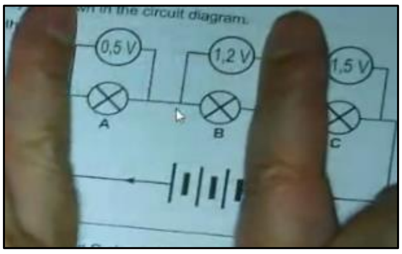


Figure 4-13 – Resistors A and B as two places where money is paid

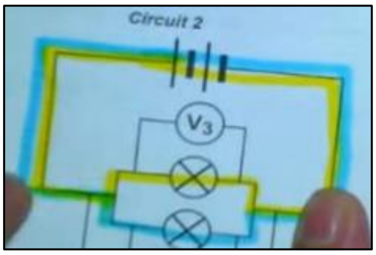


Figure 4-14 – One resistor for yellow people to pay money

… can you see that there are three places where you have to pay money?

You put your fingers like that, and you will see between A and B, there are two places where I paid money.

For the yellow people, that is the only place where I would have spent my money.

A few crucial factors require careful consideration. While there is value in creating an analogy that simplifies a complex concept such as electrical potential difference in circuit analysis, it is important that teachers acknowledge the limitations thereof. First, the people-charge analogy overlooks the important idea that at different points in the circuit, energy is being converted rather than used up. Additionally, while it may be acceptable to view electrical potential energy as more at one point (at one end of the cell) and less at another point (upon re-entering the cell), the teacher should clarify that the charges are not losing energy, but rather they are at points of lower electrical potential energy as some of it has been converted into other forms, such as heat or light. This specific analogy simply focuses on the quantitative nature of voltage through series and parallel circuits as required by the CAPS curriculum for Grade 9 learners (Department of Basic Education, 2011a). Moreover, being able to simplify ideas in order to make it more understandable and accessible is a crucial component of a teacher's PCK. However, a teacher should always exercise caution to avoid oversimplification that does not accurately reflect the truth.

Learner Understanding of Science

In the video resource, all 15 circuit diagrams analysed and discussed used the people-charge analogy to refer to voltage. Whenever learners were asked about readings on different voltmeters connected over cells or resistors, Teacher A consistently referred back to the analogy. Given the frequent use of this analogy, there is evidence of how the learners grasped it and used it in their explanations to items in the diagnostic test.

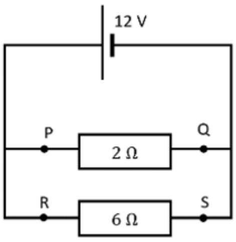
Let us re-examine Figure 4-11. Pay particular attention to the section where Teacher A mentions, "because whatever you have, you have to use to move through the circuit".

In Item 7 of the diagnostic test (Figure 4-15), 14 out of the 25 learners selected the correct option (Option D), and a few learners explained their answer by referencing the idea of voltage as energy that is gained and needs to be "used up". Three explanations are included:

> *… the voltage provided by the battery must be used by each branch.*
>
> *… both branches have to have a voltage of 12 because there is only one place for them to use it, which is between the point Q and P and point R and S.*
>
> *… the voltage received from the cell to the electrical charges has to be used up in the circuit.*

Question 7

Read the five statements below, describing current and voltage in the circuit.



i. *The current between points P and Q is greater than the current between points R and S.*
ii. *The current between points P and Q and points R and S is the same.*
iii. *The voltage between points P and Q and points R and S is both 6 V.*
iv. *The voltage between points P and Q and points R and S is both 12 V.*
v. *The voltage between points P and Q is smaller than the voltage between points R and S.*

Which of the statement/s is/are correct?

A. Only ii and iii are correct.
B. Only ii and iv are correct.
C. Only i and v are correct.
D. Only i and iv are correct.

Figure 4-15 – Item 7 of the diagnostic test

Additionally, some learners were able to explain how the combined voltage values across the resistors in series were equal to the voltage across the cell, which aligns with the analogy.

> *… in a series circuit, the voltages from other components like light bulbs and resistors add up to the total voltage over the cell/battery (the source of the energy).*
>
> *… in a series circuit, the voltages of all of the components must add up to that of the battery/cell.*
>
> *… in a series circuit, the volts across the circuit must add up to the total volts (voltmeter reading across the battery).*

It is evident that the people-charge analogy significantly helped learners understand resistors in a series circuit functioning as potential dividers. Although it is uncertain to what extent the learners have a conceptual understanding of how voltage is connected to the difference in energy that charges have between two points in a circuit pathway, it is clear from their explanations that this analogy has helped them understand the quantitative nature of voltage division in a series circuit. This is expected of Grade 9 learners at this introductory phase of electric circuits in natural science (Department of Basic Education, 2011b).

After further analysis of the learners' responses to Item 7 (Figure 4-15), a trend emerged where similar incorrect explanations were used.

In Teacher A's PowerPoint presentation, she discusses the rules of circuit analysis for parallel circuits, each on a separate slide. Figure 4-16 displays these rules as they appear as slides in her PowerPoint presentation:

- **Rule 1:** Current splits in parallel = current dividers – sum of branches = total current.
- **Rule 2:** The higher the resistance in the branch, the lower the current in it.
- **Rule 3:** The more branches, the lower the total resistance of the circuit = total current increases.
- **Rule 4/5:** The potential difference of each branch is equal and adds up to the potential difference across the battery/cell.

Attention is to be made to Rule 4/5 featuring her rule governing the behaviour of voltage in a parallel circuit.

Even though the numerical values in the diagram are correct, Teacher A inaccurately explained that the voltage values on the voltmeters across the branches in a parallel circuit add up as being equal to the total voltage across the battery. In Item 7 of the diagnostic test, a few learners used this incorrect idea to explain how voltage is distributed in parallel circuits:

> *You have to use the energy that you are given so everything has to add up to 12.*
>
> *Each branches voltage must add up to the voltage across the battery.*

This highlights how a simple mistake by the teacher can affect learner understanding. Although her diagram values are correct, her words convey a different meaning, which confused learners.

Additionally, in Rule 1 and Rule 3, Teacher A uses an equal (=) sign instead of a dash (-) which may also be confusing for learners. The inability to recognise the impact of such errors demonstrates a limited PCK quality.

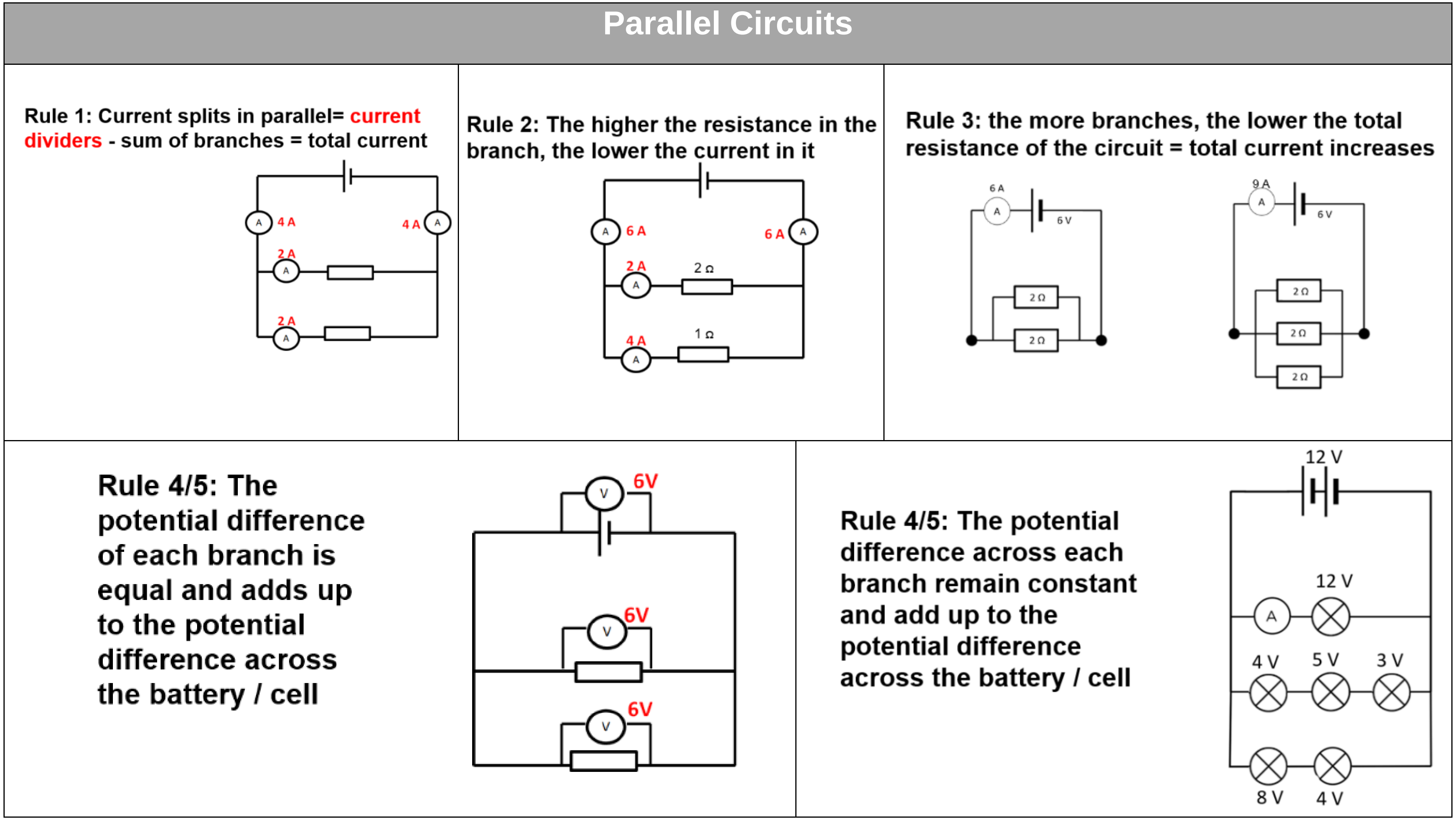


Figure 4-16 The rules of parallel circuits used in Teacher A's PowerPoint presentation

4.2.3 Representation 3 – Shop Analogy

Conceptual Teaching Strategies

Teacher A uses another analogy to help learners understand how the total resistance of a circuit decreases when resistors are added in parallel. In this analogy, she compares the branches of a parallel circuit to counters at a Pick 'n Pay store, which is a major retailer that sells food, clothing and general merchandise in South Africa. She explains how the number of open tills (counters) affects how quickly people move through the queue. Having more open tills (branches in a parallel circuit) allows more people who are already in the queue (with charges or current flow) to pay for their goods and leave the shop. Essentially, the rate at which the queue moves is related to the flow of charge through the circuit. Therefore, current (movement of people through the queue) increases when more branches (counters) are added in parallel. During the interview, Teacher A acknowledged that, although she uses this analogy to help her learners understand the concept, they still find it quite to grasp.

> *I spoke about this concept of having things in parallel will make the flow faster because the resistance is smaller because you have different branches, but they do not snap it … Yeah, that concept every year, I have to explain it numerous times. So even though I have analogies … they struggle.*

Figure 4-17 displays the PowerPoint slide that Teacher A uses with her shop analogy to explain how current is affected when resistors are connected in parallel:

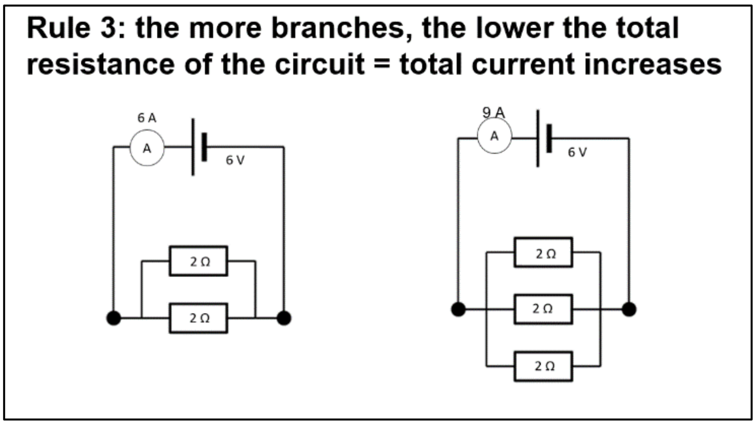


Figure 4-17 – Relationship between resistors in parallel and current

In the video resource, there was no question that specifically required an explanation as to what happens to current or an ammeter reading when another resistor is added in parallel. There is one moment in the video (Figure 4-18) when Teacher A uses only the queue part of this analogy:

> *It's like a queue of people. Here is a big fat queue and only here do they separate from each other before joining it back together again.*

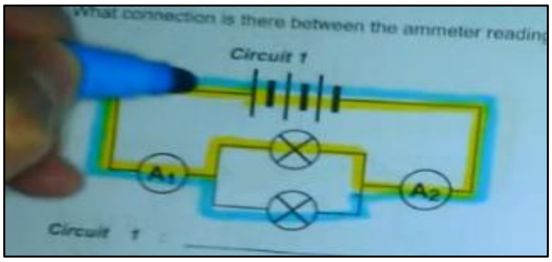


Figure 4-18 – Video extract of resistors in parallel

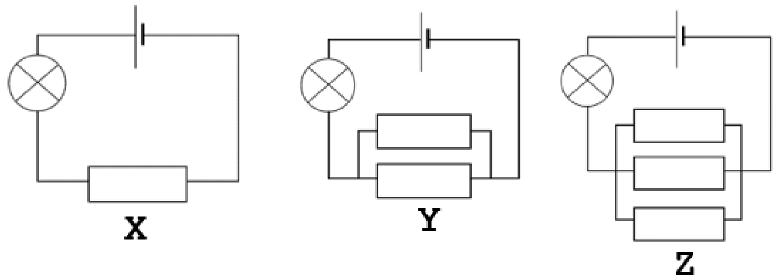
Teacher A observed that her learners enjoy and understand the application of the shop analogy in relation to current and resistance in parallel circuits when it is explained and discussed in class. However, when they need to apply this knowledge on their own, they still find it quite difficult to understand how adding resistors in parallel affects current:

> *Because if I say to them, do you remember the story I told you about Pick 'n Pay? They can explain it to me. They can tell me everything beautifully. But they can't take that and say, OK, total resistance is going to decrease. So total current will increase so where that light bulb is, the current must be higher.*

It is necessary to pause the analysis here for a brief mention on where her analogy breaks down. In this specific analogy, Teacher A explains current as the speed at which the queue moves. Current is the measurement of the amount of charge (in her analogy, the people) that moves past a point per second. The analogy might confuse some learners since they could assume that if having more branches in a parallel circuit results in a higher current flow, then having more counters in a shop will suddenly lead to more people in the queue or shop! Although her analogy may serve as a valuable representation of the relationship between resistance and current in a parallel circuit, caution should be taken to ensure that learners understand current as a quantity of charge rather than a measure of speed. This suggests that Teacher A may have limited PCK regarding how the use of this representation affects her learners' understanding regarding the effect of a parallel connection.

Question 5

In which circuit would the light bulb shine the dimmest?



A. Circuit X.
B. Circuit Y.
C. Circuit Z.
D. The light bulb will shine with the same brightness in all three circuits.

Figure 4-19 – Item 5 of the diagnostic test

Out of the six (24%) learners who selected the correct option (Option A) for Item 5 in the diagnostic test (Figure 4-19), three explanations revealed an accurate understanding of the connection between the number of resistors in parallel and total resistance. Two explanations connected this idea to current as well:

> *… the more resistors you have in parallel, the lesser the total resistance as the current will split evenly and go through the resistance much quicker.*
>
> *The more branches connected in parallel, the more pathways there are for the current to flow through meaning there is a greater current in circuit Z.*

However, out of the remaining 19 learners, 10 (40%) selected Option C, indicating they hold the parallel circuit misconception where learners think that the more resistors are added in parallel, the higher the resistance. Meanwhile, nine learners (36%) selected Option D, suggesting they believe that a change in the parallel connection will not affect the brightness of the bulb. The following learner explanation for selecting Option D reveals an important conclusion about how Teacher A's colour-coding representation has led to a misunderstanding about the effect of resistors connected in parallel:

> *… no matter how many resistors are added, the brightness will remain the same because each pathway only has one resistor and a light bulb so it is the same through all the paths so it doesn't affect the brightness.*

This is an important finding since it reveals how easy it is for teachers to unconsciously create misconceptions in their learners' understanding of electric circuits. First, using colours makes it easier for learners to visualise the various paths that electrons take as they move through a circuit, helping them understand how charges distribute their energy through the resistors in their path. However, when it comes to understanding what effect connecting more resistors in parallel has on the magnitude of the overall current of the circuit, this colour-coding techniques actually creates a misconception: since each charge still only goes through one resistor, regardless of how many more are added in parallel, no change is made to the rest of the circuit and thus the brightness of the bulb does not change. Another learner responded similarly and was not able to relate this idea to current either:

> *The electrical charges lost the same amount of energy before it went to the light bulb. The light bulbs thus all shine the same.*

Some learners have not made the connection between the larger or overall effect that connecting resistors in parallel has on the rest of this circuit. This could be because Teacher A has not clarified the limitations of her representation, failing to explicitly indicate where the representation is effective and where it falls short. Consequently, learners misunderstand parts of this concept because Teacher A is not fully aware of these limitations and has not communicated them to the learners. As a result, Teacher A should continue to develop her PCK when it comes to identifying the strengths and weaknesses of her representations. She should be explicit about bringing such limitations to her learners' attention in case it leads to misunderstandings as revealed above.

While it was clear that the people-charge was effective in helping learners understand the circuits that they had in front of them, there is minimal evidence to suggest that the shop analogy had the same effect. The shop analogy was explained in class, and repeated a few times, with one opportunity given to apply it (Figure 4-20) before it was addressed in the diagnostic test. Based on the results of the diagnostic test and the evidence of the repetitive use of the people-charge analogy and colour coding, it can be concluded that the repeated use of a representation directed at one specific idea makes a significantly larger impact on conceptual understanding of learner knowledge than simply using a representation once or twice.

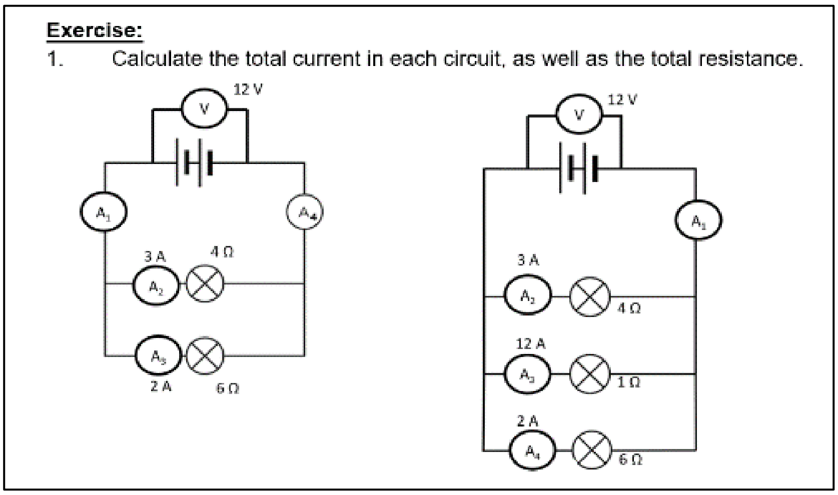


Figure 4-20 – Example in the circuit rules documents made by Teacher A as practice

4.2.4 Representation 4 – Definition and Corresponding Formula

Conceptual Teaching Strategies

Teacher A believes that learners should have a solid, foundational understanding of what each concept – current, voltage, and resistance – represents in the context of electricity before exploring the quantitative (proportional) relationships between the three. Teacher A suggests that it is important to introduce learners in Grade 9 to the proportional relationships between resistance and current, as well as between resistance and voltage (Department of Basic Education, 2011a). However, she specifically ties the in-depth understanding of the relationships between current and voltage to the selection of physical science as an elective in Grade 10, since they only address Ohm's Law in Grade 11. This implies that learners who choose to pursue physical science will delve deeper into how these concepts relate to each other, aligning with their elective preferences and interests. Teacher A exhibits high quality PCK regarding the place of the topic in the curriculum. She is able to logically sequence important ideas and justify how they are all interrelated at different stages throughout the learning journey or course.

To reinforce understanding, Teacher A uses a teaching strategy that involves repeating and reiterating the formal definitions of current, voltage, and resistance together with the mathematical representation of these concepts through relevant formulae. The definitions and corresponding formulae are written on the whiteboard whenever a concept is addressed in a topic:

Every time I talked about the concept, I put that formula on and then I wrote it in words next to it. So, energy for every charge. And the number of charges moving in one second …

Figure 4.21 and Figure 4.22 show Slide 23 and Slide 40, respectively, of Teacher's A PowerPoint presentation. It illustrates how she aligns the formal definition of current and voltage with their corresponding mathematical formulae. This effectively demonstrates that the mathematical representation simply presents the definition in an alternate format, and therefore unifies the formula and definition.

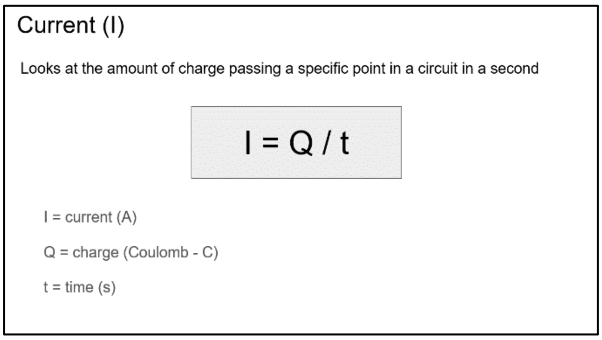


Figure 4-21 - Slide 23 of Teacher A's PowerPoint presentation

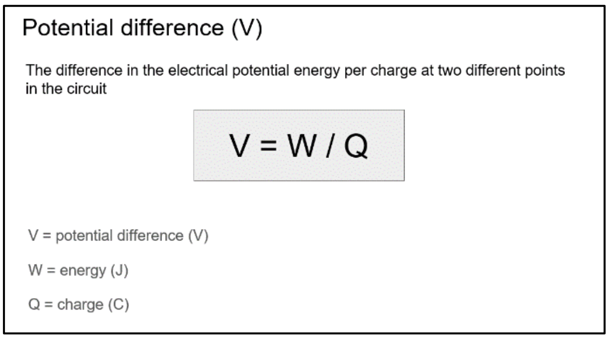


Figure 4-22 – Slide 40 of Teacher A's PowerPoint presentation

Teacher A's use of these formulae, while knowing that it is out of scope, reflects her knowledge of learner understanding as a component of PCK. Teacher A has deemed it important for her learners to understand that voltage is an energy concept, while current is charge per time. This knowledge will ensure an accurate understanding of the difference between these concepts at a later stage in the learners' physical science journey through school. Therefore, even though she gives the concepts only as much attention as they deserve at Grade 9 level, she presents it in such a way that it benefits the learners' overall understanding and prepares them for future learning. As a result, her PCK in this component of knowledge of the place of content in the curriculum and how they are related to each other is seen as high quality (Mazibe et al., 2023).

Additionally, the two formulae, including Ohm's Law for resistance, feature at the very beginning of the circuit rules document that Teacher A distributed to her learners (Figure 4-23). This suggests that, in following a systematic approach through the document, she first discusses and explains the formulae and then applies them in various calculations as required throughout the worksheet.

Important electricity formulae:

$R = \frac{V}{I}$ | $I = \frac{Q}{t}$ | $V = \frac{W}{Q}$

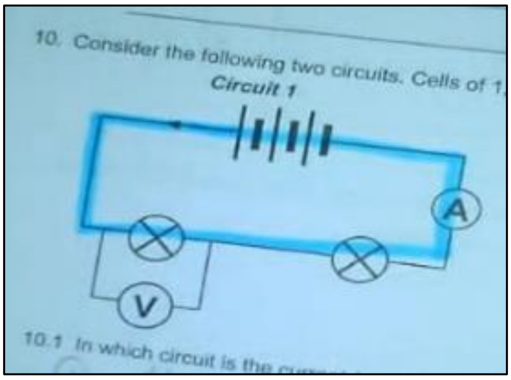
R = resistance (Ω)
V = potential difference (V)
I = current strength (A)

Q = charge (C)
t = time (s)

W = energy (J)

Figure 4-23 – Beginning of the circuit rules document made by Teacher A

In the video she made for her learners, Teacher A discusses how the voltage is distributed across the resistors in the very first circuit diagram. She presents the definition of voltage as it appears in the mathematical equation ($V = \frac{W}{Q}$) and then uses her people-charge analogy to emphasise resistors as potential dividers. Figure 4-24 shows a screenshot of this circuit diagram with the corresponding audio:



*Now, for Question 10.2, if we think of the potential difference, it looks at **energy per charge**, like we've been talking about… (then analogy 2)*

Figure 4-24 – Video extract where Teacher A uses the explanation

Learner Understanding of Science

In the diagnostic test, when asked to explain how the concept of voltage is understood, some learners were able to relate this idea to energy that charges/electrons have at different points in a circuit, responding with:

> *Voltage is the **amount of energy** supplied or lost to **each electrical charge** in a circuit.*
>
> *Voltage is the difference in amount **of energy per charge** between two points.*

However, there were also responses that revealed that some learners still do not completely understand how voltage and current are two separate ideas, with some responses being:

> *Voltage is the difference in electrical current between two points.*

Voltage is the comparison of the current before and after the resistor (the difference).

Voltage is the amount of current/energy a component in a circuit needs to work.

Despite repeating and reiterating the definition and formula for current strength ($I = \frac{Q}{\Delta t}$) and voltage ($V = \frac{W}{Q}$) on a regular basis, the actual formulae were not used for formal calculations due to it being beyond the scope of the curriculum. Instead, the formulae were used exclusively to help the learners remember the definition of current and voltage.

Resistance, and the equation to calculate it, $R = \frac{V}{I}$, was the only equation used for calculations in this topic (although also not in scope for Grade 9 either), and even this equation was primarily used when a rule could not be applied to find a numerical answer. Teacher A notes that this approach provides a sense of security for her learners, offering a clear direction when they may feel stuck. She elaborates on this approach, stating, "If you can't find something with a rule, then you go over to *V*, *I*, *R*".

Figure 4-25 captures a particular segment of the video where Teacher A repeatedly rewrites the equation to calculate resistance ($R = \frac{V}{I}$) to demonstrate to her learners the factors that can affect the total resistance of the circuit.

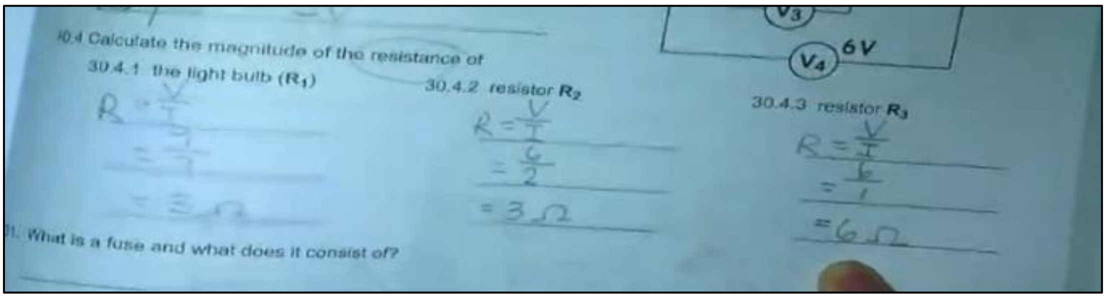


Figure 4-25 – Video extract showing where Teacher A uses equations

4.2.5 Other Representations

The following representations that Teacher A used in the teaching of electric circuits are categorised as secondary representations, since they were not used as prominently as the ones previously discussed. While there is limited evidence regarding the connection between the use of these representations and learner understanding of the concepts addressed in the diagnostic test, it is important to acknowledge the variety of teaching strategies and methods employed by Teacher A.

A brief discussion on the purpose of the representation for each of the following secondary representations is conducted, including how the representation was used in the teacher's teaching methods, as well as any possible connections it may have had with the learners' responses in the diagnostic test.

Discussing Redox Reactions as an Introduction to Electrical Potential Energy

Teacher A uses the standard reduction potentials table (shown in Figure 4-26) at the beginning of her teaching programme to introduce voltage as an energy difference that the charges (electrons) have when they move from one place to another.

Half-reaction			E°/volt
$Li^+ + e^-$	$\rightleftharpoons$	Li	−3,05
$K^+ + e^-$	$\rightleftharpoons$	K	−2,93
$Cs^+ + e^-$	$\rightleftharpoons$	Cs	−2,92
$Ba^{2+} + 2e^-$	$\rightleftharpoons$	Ba	−2,90
$Sr^{2+} + 2e^-$	$\rightleftharpoons$	Sr	−2,89
$Ca^{2+} + 2e^-$	$\rightleftharpoons$	Ca	−2,87
$Na^+ + e^-$	$\rightleftharpoons$	Na	−2,71
$Mg^{2+} + 2e^-$	$\rightleftharpoons$	Mg	−2,37
$A\ell^{3+} + 3e^-$	$\rightleftharpoons$	$A\ell$	−1,66
$Mn^{2+} + 2e^-$	$\rightleftharpoons$	Mn	−1,18
$2H_2O + 2e^-$	$\rightleftharpoons$	$H_2(g) + 2OH^-$	−0,83
$Zn^{2+} + 2e^-$	$\rightleftharpoons$	Zn	−0,76
$Cr^{3+} + 3e^-$	$\rightleftharpoons$	Cr	−0,74
$Fe^{2+} + 2e^-$	$\rightleftharpoons$	Fe	−0,44
$Cd^{2+} + 2e^-$	$\rightleftharpoons$	Cd	−0,40
$Co^{2+} + 2e^-$	$\rightleftharpoons$	Co	−0,28
$Ni^{2+} + 2e^-$	$\rightleftharpoons$	Ni	−0,25
$Sn^{2+} + 2e^-$	$\rightleftharpoons$	Sn	−0,14
$Pb^{2+} + 2e^-$	$\rightleftharpoons$	Pb	−0,13
$Fe^{3+} + 3e^-$	$\rightleftharpoons$	Fe	−0,04

I told them it's a redox reaction. I told them electrons are going to move. And that one (metal) gives away electrons more easily than the others. And I say that if you now have that, it gives the charges energy … energy per charge.

Figure 4-26 – Standard reduction potentials table used by Teacher A

Figure 4-27 is a slide from Teacher A's PowerPoint presentation, which she uses to explain the origin of this energy difference.

The inside of a dry cell

- Two **electrodes** (cathode and anode) made from different materials
- **Electrolyte** (solution / paste) that can conduct electricity because it contains ions
- As soon as you put the cell in the circuit the reaction take place
- Charges move via external circuit
- Chemical energy is converted to electrical energy (moving charges - so this includes kinetic energy)

Figure 4-27 – Slide used in conjunction with standard reduction potentials table

During the interview, she mentioned that certain learners found this explanation confusing and clarified that she included it in response to a specific question in the learners' textbook that lacked sufficient explanation. Since voltage or potential difference is outside the scope of

Grade 9, except for the quantitative nature of voltage in series and parallel circuits (Department of Basic Education, 2011a), this model was solely used to introduce voltage as an energy concept. The people-charge analogy, which linked voltage to the amount of money spent at various points along a journey (path), proved to have a more substantial impact on learners' understanding than this explanation of a redox reaction. There is no direct evidence in the diagnostic test that indicates a connection between this representation and the learners' responses related to voltage. Based on the insights provided by the teacher regarding how learners struggled with the concept of voltage throughout the teaching programme coupled with the prevalence of responses indicating confusion between voltage and current, it is my contention that the early introduction, or indeed any introduction, of redox reactions heightened confusion or created misunderstanding.

This is another display of the teachers' PCK in this topic. Since she understands that electrons receive their electrical potential energy from the chemical potential energy inside the cells, she believes that is the optimal starting point. Although accurate, her PCK begins to break down in her knowledge of learner understanding. At Grade 9 level, her learners have no prior knowledge of redox reactions, let alone the fact that different chemical reactions produce varying amounts of energy. As a result, because this explanation was used to explain the energy part of voltage, learners now associate their lack of understanding of redox reactions with voltage, thus rendering a challenging concept even more complicated.

Using Electric Circuit Kits and PhET Simulation

An important part of developing a solid conceptual understanding of concepts in electric circuits involves engaging in practical, hands-on activities (Kapici et al., 2019). For this topic, this would involve using circuit boards or kits with wires, light bulbs and cells, among others, to construct different arrangements of series or parallel circuits. While Teacher A recognises the significance of exposing learners to such practical activities, she has previously found that learners find the operational side of working with circuit boards a challenge. This includes reading meters correctly, connecting components suitably, and working with components that are faulty. As a result, this year, Teacher A opted to rather use a PhET simulation to perform the same investigative procedure as the learners would have done with physical circuit boards because she found that "if you want to do rules properly, then the PhET simulation is easier and faster and it will do what you want it to do". This was a guided activity where Teacher A "set up a whole exercise where they had to follow the instructions, build it, find all of the values, then link it with each other". She did not provide evidence of this task.

Teacher A still provided one opportunity for her learners to work with circuit boards. For this practical task, her learners investigated the factors that can affect resistance (such as length, type of material, temperature, and thickness) and also connected an ammeter in series to observe how the current changes in each case. The diagnostic test revealed that learners exhibited a more thorough understanding of the relationship between current and resistance compared to their understanding of the relationship between voltage and resistance or current. It is possible that this discrepancy may be attributed to learners relating to the former relationship both theoretically and practically, which highlights the effectiveness of this dual approach.

Conclusion

Overall, Teacher A demonstrates a sound knowledge of learner understanding, recognising the essential concepts for her learners and understanding the interconnectedness across different grades. However, while her use of representations, particularly the colour-coding technique, was an effective aid in getting learners to understand how electrons move throughout different parts of a circuit, there are some notable limitations that are worth refining. Since Teacher A was not explicit in identifying the limitations of her representations and did not have an accurate idea how this influenced the understanding of the content, her PCK about both learner understanding and representations as CTS requires further development.

4.3 Results of Teacher B

Teacher Description

Teacher B teaches science to learners at a private school in Collaroy, Australia. Proficient in English, she has six years of experience in teaching high school science, specialising in Grade 11 and Grade 12 chemistry. In this school, high school learners from Grade 7 to Grade 10 are placed into classes based on their gender and academic performance from the previous year. Teacher B taught a class of eight Grade 9 learners with middle to low academic abilities, along with other classes. The topic of electric circuits was taught to this class over a two-week period towards the end of Term 2 in 2023. Although Teacher B was aware of the outcomes that she needed to achieve, she did not have a formal lesson plan that dictated what she should do in each lesson. During the interview, she described how she allowed the learners' responses to lesson activities guide her teaching. Based on learners' questions and feedback, she said she was able to instantly identify their misconceptions and what conceptual connections still had to be made, which she then addressed and used to direct her ongoing instruction:

> *Well, in a way I didn't have a lesson plan – like a lesson plan as to this is what I'm going do, if this goes wrong, then this is my backup plan. I kind of let the students guide me as to what I needed to inform them in terms of the misconceptions and what bridges in their knowledge they needed to have.*

When prompted in the interview about how she would approach the topic of electric circuits, she considered both the behaviour and academic abilities of her learners before she committed to a particular teaching strategy:

> *Because I have the boys' class, I have this assumption in my mind that "Oh!", like knowing the kind of calibre that they are and the boys really like to construct and do things. It's possible that they've done this for ages and ages and ages, so I wanted to do it in a different way. And with my kind of class I can't, like, let the slightest thing go wrong with them, because otherwise, chaos will reign through.*

She opted for a teaching strategy in which the tasks that were provided to her learners were simple (making it easy to succeed by understanding) and inquisitive (making discovery attainable and fun). By understanding her learners and how they learn, Teacher B displayed the application of one of the seven Australian Teacher Professional Standards (Government, 2018) as well as the use of her PCK. Part of this knowledge involves customising instruction based on learners' prior knowledge, misconceptions, and developmental levels in order to make it more accessible and comprehendible (Park & Oliver, 2009).

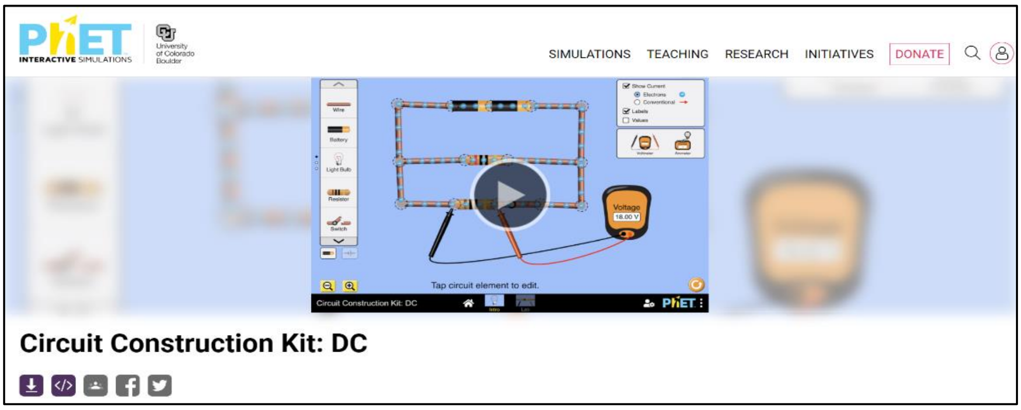


Figure 4-28 – Front page of the electric circuit simulation used by Teacher B

The data sources for this analysis include the information gathered in the interview with Teacher B, the findings from the results of a diagnostic test completed by her learners, and additional materials provided by Teacher B. The additional materials include the name of the online simulation that she used when teaching this section, namely *PhET Interactive Simulations: "Circuit Construction Kit: DC Circuits"* (Figure 4-28) and three worksheets. One worksheet (Annexure D) was obtained from a website that provides various teaching resources (Twinkl, n.d.) and the other two (Annexure E and Annexure F) were drawn from resources that she had gathered throughout her teaching career and personally edited to suit the needs of this lesson structure. This was the first time that Teacher B used the PhET simulation in her entire science career. During the interview, she mentioned that she believed that using physical circuit kits could create a more disruptive class environment. Teacher B thus used only **one representation** (a combination of PhET and complementary worksheets) apart from diagrams drawn on paper or a board as CTS when teaching the topic of electric circuits to her Grade 9 learners.

What follows is a three-part analysis of how each worksheet was used together with the PhET simulation as a representation that Teacher B used in her teaching of electric circuits. These three parts, which have been presented under the two components of teacher PCK as discussed in the conceptual framework, include knowledge of:

- **Conceptual Teaching Strategies**
  - What the representation is and how the teacher used it in in class.
- **Learner Understanding of science**
  - Learner knowledge about electric circuits.
  - Whether a connection exists between the CTS used by the teacher and how the learners understand the concepts of electric circuits.

4.3.1 Worksheet 1 – Interpreting and Drawing Circuit Diagrams

Conceptual Teaching Strategies

During the interview, Teacher B described how she approached teaching this topic. She mentioned how she wanted to keep the introductory lesson simple. She started the lesson with a worksheet that enabled learners to familiarise themselves with circuit symbols and circuit diagrams. By doing so, she "introduced them to what circuits really were" and used this time to "get some ideas [and initiate] a lot of like discussion (around) their background knowledge of circuits".

Teacher B mentioned a simple matching activity where learners had to match the components of an electric circuit with their corresponding circuit symbols. However, this resource was not presented to the researcher. Teacher B did provide a worksheet as evidence for the introductory part of her teaching, titled *Interpreting and Drawing Circuit Diagrams*, which is presented in Annexure D. The worksheet instructed learners to label the various parts of a circuit diagram and then create their own diagrams using scientific symbols when given pictures of different components. Teacher B found that most of her learners completed the worksheet with success.

As part of this introductory activity, Teacher B had her learners access the online PhET simulation (Figure 4-28) on their own electronic devices, and she gave them some time to make a few discoveries about how the simulation works on their own. The final part of this exploration phase involved getting learners to use the simulation to construct some of the circuit diagrams that appeared on the worksheet. Afterwards, they discussed their observations:

> *Well, I got them to play with it. And I said after they had done this, they now actually construct those diagrams and what can you see and by the end of that it was the end of the lesson.*

Teacher B has identified a suitable representation for this stage of her teaching. She has been able to outline some of the key concepts (identifying circuit symbols and drawing circuit diagrams) and sequence her ideas to fit within her broader teaching plan. Furthermore, by accessing learners' prior knowledge, identifying some of their misconceptions, and using these to inform her future instruction, the part of her PCK that reflects her knowledge of learner understanding of science can be seen as high quality (Poti et al., 2022).

Learner Understanding of Science

Teacher B found that the learners already had a good understanding of circuit symbols and diagram besides that of a resistor:

> *The majority of my class could do those really well. The only one they had problem with was probably the resistor.*

In the interview, she mentioned that this basic knowledge was already covered in Grade 8. Learners were familiar with series and parallel circuit connections, however, none of these have involved resistors as opposed to light bulbs.

Since there is no opportunity for learners to draw circuit diagrams in the diagnostic test and teachers were given the freedom to tell the learners what the symbols were in each of the circuit diagrams given in the diagnostic test, it is challenging to determine whether this worksheet as a representation had a direct impact on how learners responded to the items in the diagnostic test.

4.3.2 Worksheet 2 – Electrical Currents: Part 1

Conceptual Teaching Strategies

After covering the basic ideas of circuit symbols and diagrams, Teacher B focused on the concept of current in both series and parallel circuits. She confirmed that, during this time, her learners were each given their own copy of the worksheet titled *Electrical Currents* (Annexure E) and were instructed to use their personal electronic devices to access the PhET simulation and complete the worksheet. Teacher B has systematically structured this worksheet in a way that highlights the four key concepts about current that she intends her learners to understand. The structure of the worksheet is summarised in words below but was mostly presented in the format of circuit diagrams.

Worksheet 2, Part A, addressed the following concepts:

Concept 1: Current/brightness when more light bulbs are added in series

> Learners were instructed to: Use the simulation, construct two series circuits: one with a light bulb, cell, and ammeter, and another with an additional bulb. Record observations on bulb brightness and current on the worksheet, attempting to connect these ideas.

Concept 2: Current/brightness in series vs parallel

> Learners received the following instructions: Using the simulation, construct a series and parallel circuit with two light bulbs, a cell, and an ammeter. Note observations, compare brightness of bulbs, and complete a **cloze passage** summary of differences between series and parallel circuit connections.

Concept 3: Compare current at different parts of a series circuit

Learners received the following instructions: Using the simulation, construct a series circuit with three light bulbs, a cell, and three ammeters (one between each bulb) and record these readings on the worksheet.

Concept 4: Compare current at different parts of a parallel circuit

Learners received the following instructions: Using the simulation, construct a parallel circuit with two light bulbs, a cell, and three ammeters (one in the main branch and one in each parallel branch) and record these current readings on the worksheet.

Write conclusions about current in both series and parallel circuits, representing each as a formula.

At this point in the analysis, it is appropriate to draw attention to two important errors in this worksheet. First, in the cloze passage (Figure 4-29), where learners are required to summarise their findings of the main difference between series and parallel circuit connections (Concept 2), the use of the words “side by side” as a way of connecting components in parallel may create a misinterpretation since this could also be true for components in series.

In a .... circuit, the components are .... side by side. This gives the current several different .... for it to flow around. If one bulb blows, the other bulbs will .... lit as the circuit is still complete. In a series circuit, the .... are connected end to end in a .... If one bulb breaks, the whole circuit will go .... and none of the bulbs will light as the circuit is .... complete.

out	parallel	remain	loop	not	paths	connected	components

Figure 4-29 – Cloze passage in worksheet (Annexure E)

A second error can be seen in Concept 4. Learners need to connect ammeters to various parts of a parallel circuit to determine how current splits in a parallel circuit (Figure 4-30). The placing of ammeter A_1 is in the main branch instead of the first branch directly next to the light bulb. It is assumed that, unless Teacher B informed the learners about this error, the learners would not be able to fully understand how current splits in a parallel circuit.

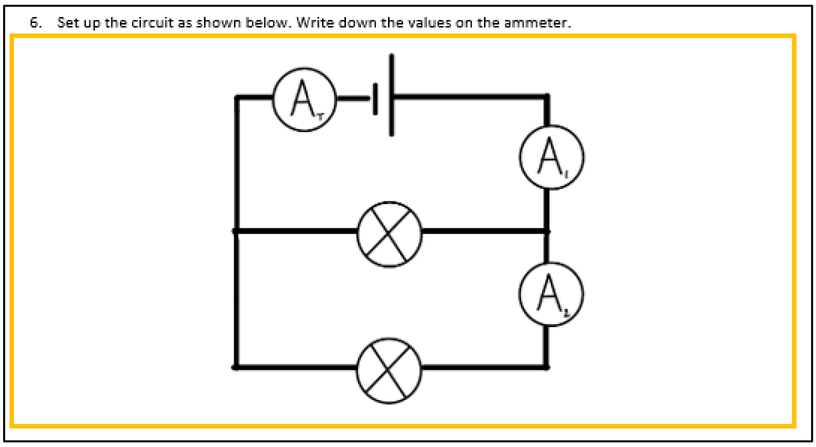


Figure 4-30 – Current in parallel connections from worksheet (Annexure D)

During the interview, Teacher B revealed that she implemented an inquiry-based approach by using a combination of this worksheet and the PhET simulation. Her goal was aimed at "giving them … different ways to actually look at constructing circuits" and expressing their understanding both qualitatively (by writing down observations) and quantitatively (by looking at the ammeter readings and constructing formulae).

During the interview, she mentioned the main purpose of the worksheet and simulation and described her role in this strategy:

> *It was all inquiry based so I actually didn't help them at all with this. It was all just: "Can you actually figure out the patterns?" And my role to them was they would ask me questions.*

She elaborated on her understanding of a learner-centred lesson:

> *I think everyone gets confused. I think "inquiry" is very student focused but really, it is student focused in a way where that you have to, as a teacher, kind of facilitate what's going on, to build it off their discussions and their questions and really pull it out of the students as well.*

During the interview, she finally pointed out that her learners understood series circuit connections much better than parallel circuit because series circuit make more sense to them and they were easier to construct in the PhET simulation than parallel circuits. Additionally, the simulation made it straightforward to observe the difference in the brightness of the light bulbs, especially in series circuits (Figure 4-31).

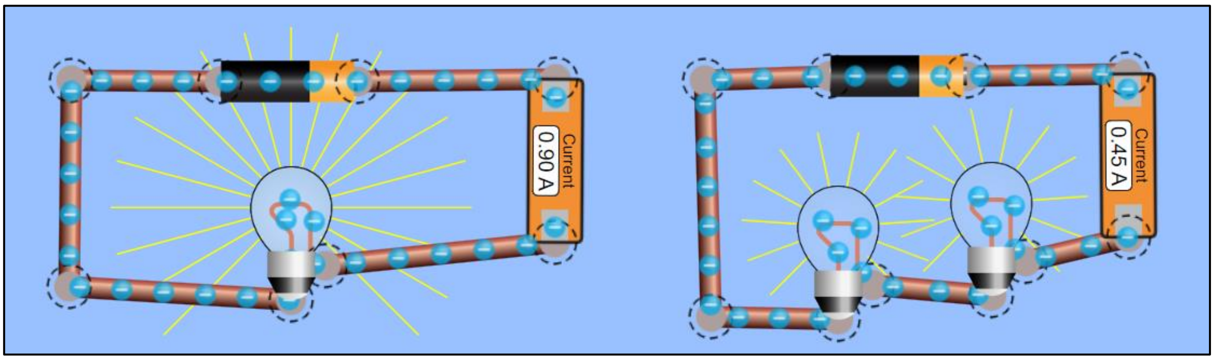


Figure 4-31 – Difference in brightness of light bulbs as shown in the PhET simulation

During the interview, Teacher B revealed a thorough understanding of sequencing different ideas in the topic of teaching electric circuits. When discussing the direction of current, she emphasised how she purposely decided against teaching the concept of conventional current, considering it too complex for Grade 9s. She believed that it is best reserved for senior years. More importantly, she highlighted that her learners have not properly defined and grasped the nature of electrons and their origins, which her school planned for her to teach later in the year, following the instruction on electric circuits.

> *I don't think they actually know what an electron is. Because they don't look at the atom until they get to Year 9 chemistry – because they're about to do it now.*

Here, Teacher B demonstrated a solid knowledge of the concepts that form part of a basic understanding of current electricity (like electrons being charge carriers) and recognised their foundational importance in the curriculum. As a result, the PCK revealed here is sound since it demonstrates her ability to sequence key ideas effectively and understand the inter-relatedness of concepts within the topic (Mazibe et al., 2023)

Learner Understanding of Science

Eight learners in Teacher B's Grade 9 science class completed the diagnostic test. The data used to assess the impact of the representation (combined use of Worksheet 2 and simulation) on learners' understanding of concepts in electric circuits, was sourced and analysed from their responses to specific items in the diagnostic test that are related to the four main concepts in Worksheet 2.

Concept 1: Current/brightness when more light bulbs are added in series and Concept 3: Compare current at different parts of a series circuit

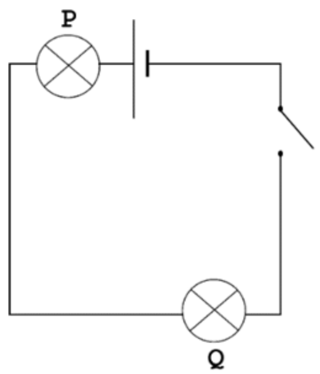
The results of Item 2 of the diagnostic test reflect that learners in this class seem to understand the conditions that need to be met in order for current to flow. In this item, learners are asked to determine what happens to current when one light bulb connected in series to others burns out. All but one learner identified that none of the light bulbs would shine because there is a break in the circuit and/or the circuit is no longer complete. This idea was directly addressed in the cloze passage of the worksheet that the learners had to complete during the lesson that covered current topics. Additionally, the PhET simulation clarifies the conditions for light bulbs to shine, such as a closed circuit, since every circuit that they built in the worksheets required them to have a closed circuit with shining light bulbs.

On the other hand, the distribution of current through the various components of a series circuit is not understood well. This is revealed in Item 3 of the diagnostic test (Figure 4-32). Only three of the eight learners (38%) selected the correct answer (Option C), with only one of the reasons for this selection being partly accurate:

> *The electrons are already in the circuit but they just aren't moving, so when the circuit is completed they will start moving again through the circuit.*

Question 3

In the circuit below, all the bulbs are identical. Compare the brightness of the light bulbs the moment that the switch is closed.



A. P is the brightest and Q is the dimmest and P shines before Q does.

B. P is the brightest and Q is the dimmest, and both light bulbs light up at the same time.

C. P and Q have the same brightness and both light bulbs light up at the same time.

Figure 4-32 – Item 3 of the diagnostic test

The remaining five learners (62%) selected either Option A or Option B, where light bulb P is brighter than light bulb Q. Learners understand that the circuit needs to be closed for current to flow but do not regard this current flow as constant or the same through different parts.

Additionally, some of the reasons that the learners provided for this incorrect selection revealed that their understanding of the difference between current and voltage is blurred. These reasons included:

> *This is because the voltage is decreased after the first light bulb leading to Q being dimmer and P will turn on before Q does as they are in series.*
>
> *The bulbs are in series. Therefore, P will be brighter as the voltage is the greatest.*

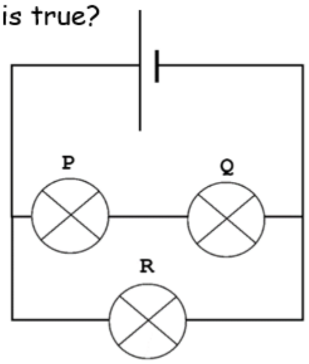
While it is not incorrect to connect the concept of voltage with current (as one does to understand the concept of electrical power), doing so prematurely may lead to confusion. Since the worksheet that Teacher B provided contains an investigation of both current and voltage, it is uncertain whether these two concepts were investigated by the learners in the same lesson or in two different lessons. However, it does provide insight into a possible source of such confusion.

Concept 4: Compare current at different parts of a parallel circuit

In Item 4 of the diagnostic test (Figure 4-33), seven of the eight learners (88%) correctly identified that the current through two light bulbs in series is the same, despite the belief that one light bulb shines brighter than the other as revealed in the previous item. This means that learners are perhaps treating current flow and brightness of light bulbs as two separate ideas.

Question 4

In the circuit below, all the light bulbs are identical. Which one of the following statements is true?



A. The current in P is greater than the current in Q.
B. The current in P is greater than the current in R.
C. The current in P is the same as the current in Q.
D. The current in P is the same as in Q and as in R.

Figure 4-33 – Item 4 of the diagnostic test

During the interview, Teacher B connected the inability to reason scientifically in a written format to inadequate scientific literacy skills. She believed that "verbally they can do it, but when it's written, they really can't", and that staff should be better trained in order to teach learners how to explain their ideas well in writing. Teacher B added that her learners were tempted to use the PhET simulation while completing the test. While this may have aided them in selecting the correct answer, it would again not allow them the opportunity to reason scientifically, which is a skill that she wished to encourage.

It is important to note that Teacher B's awareness of her learners' lack of scientific literacy reflected her knowledge of learner understanding of science as a component of her PCK. Poti et al. (2022) described the characteristics of sound PCK as the ability to recognise concepts and skills that learners find challenging, assign reasons for their difficulties, and offer suggestions for improvement. For these reasons, Teacher B's PCK for this activity can be deemed sound.

4.3.3 Worksheet 2 – Electrical Currents: Part 2

Conceptual Teaching Strategies

The second part of the worksheet titled *Electrical Currents* focused on potential difference or voltage in both series and parallel circuits. Teacher B structured this part of the worksheet in a way that highlighted two main ideas about voltage in series and parallel circuits that she intended for learners to understand. The structure of the worksheet is summarised in words below, but was mostly presented in the format of circuit diagrams (See Annexure E).

Worksheet 2, Part B, addressed the following concepts:

Concept 5: Voltage distribution across components connected in series

> Learners were instructed to: Use the simulation to first construct a series circuit with a light bulb, cell, ammeter, and voltmeters connected over the cell and the light bulb. Then, add a light bulb in series to this circuit with a voltmeter over this light bulb. Record the readings in both circuits and any observations on the worksheet.

Concept 6: Voltage distribution across components connected in parallel

> Learners were instructed to: Use the simulation to construct a parallel circuit with two light bulbs, one cell, and an ammeter in the main branch, then connect a voltmeter over each light bulb and the cell. Record the voltmeter readings and observations on the worksheet.

Write conclusions about voltage in series and parallel circuits, representing each as a formula.

Learner Understanding of Science

To determine how the worksheet supported learners' conceptual reasoning and understanding, items in the diagnostic test that relate to or address some of the two main concepts outlined above are compared and analysed accordingly.

Concept 5: Voltage distribution across components connected in series

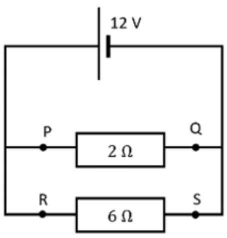
Since there were no items in the diagnostic test that explicitly addressed voltage distribution across components connected in series, only voltage distribution across components connected in parallel could be analysed and used in finding more connections between the representation used (worksheet and simulation) and learner knowledge.

Concept 6: Voltage distribution across components connected in parallel

The idea that the voltage across each resistor connected in parallel is the same value as the voltage across the battery was well understood by the learners according to their responses in the diagnostic test, however their understanding remained procedural in nature. This is first evident in Item 7 of the diagnostic test (Figure 4-34).

Question 7

Read the five statements below, describing current and voltage in the circuit.



i. *The current between points P and Q is greater than the current between points R and S.*
ii. *The current between points P and Q and points R and S is the same.*
iii. *The voltage between points P and Q and points R and S is both 6 V.*
iv. *The voltage between points P and Q and points R and S is both 12 V.*
v. *The voltage between points P and Q is smaller than the voltage between points R and S.*

Which of the statement/s is/are correct?

A. Only ii and iii are correct.
B. Only ii and iv are correct.
C. Only i and v are correct.
D. Only i and iv are correct.

Figure 4-34 – Item 7 of the diagnostic test

While seven of the eight learners (88%) chose the correct option, their explanations revealed a lack of ability to reason scientifically and fully explain ideas, especially where reasoning with voltage was concerned. Their responses were brief, with some learners avoiding an explanation altogether.

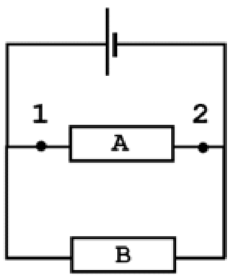
> *(i) is correct because the resistance is less. (iv) is correct because it is 12 V.*
>
> *Less resistance, more current. Voltage is the same in parallel.*
>
> *1 and 4 were both right.*

The same responses are seen in Item 6 of the diagnostic test (Figure 4-35). Five of the eight learners (63%) selected the correct option (Option C), but their reasoning lacked evidence of a conceptual understanding:

> *Because it's in parallel.*
>
> *Removing resistor B won't affect the voltage across points 1 and 2.*
>
> *A and B are in parallel; thus voltage is distributed evenly. Removing a resistor will not impact the potential difference.*

Question 6

What will happen to the potential difference between points 1 and 2 if resistor B **is removed**?



A. Increase.

B. Decrease.

C. Remain the same.

Figure 4-35 – Item 6 of the diagnostic test

During the interview, Teacher B revealed how she spent some time in a lesson distinguishing between current and voltage. She recalled that her learners, and many of the learners to which she taught the same topic to in the past, struggled with recognising just how these concepts differ from each other. When prompted about how she attempted to explain the two concepts to her learners, she described the following moment in class:

> *[In] the next lesson, what I did was, I actually said "Right, like, let's get this all out. Now tell me, what did you notice was the difference between the current and the voltage" and they were like "They were very different numbers" I said "Well, yeah, that's because the current really is a measure of how much the electrons are moving in time while the voltage is really how much force is being used to push those electrons to start to move".*

Additionally, she recalled a time where she used an acting analogy to further reinforce this pushing effect of voltage:

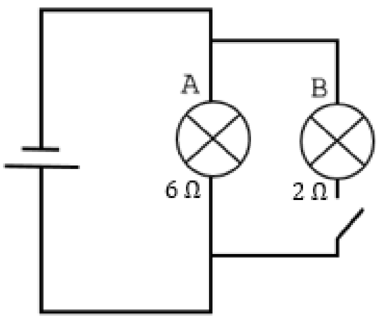
> *Let's pretend you're a circuit. And I said one person was the battery and one person was the voltage in the battery. So, they actually push them, and they had to start like doing it, kind of like a domino effect.*

It is important to note that describing the role of voltage as having a domino effect is fundamentally incorrect and fosters immediate misconceptions. This analogy misleadingly represents voltage as a force exerted by the cell on the nearest electron, which then transfers the force to the next electron in sequence. Teacher B's attempt to acknowledge or address misconceptions through the use of this representation is counterproductive as she in fact used a representation to create a misconception. As a result, this reflects a limited understanding of PCK (Mazibe et al., 2023).

Interestingly, the effect of the use of this representation can be seen in learners' responses to Item 9 of the diagnostic test (Figure 4-36).

Question 9

Consider the circuit below, with two bulbs A and B with resistances as indicated in the diagram. Select the statement below that is true.



A. When the switch is closed, light bulb A will not shine.
B. If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would no longer shine.
C. If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would still shine but slightly dimmer.
D. If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would still shine with the same brightness.

Figure 4-36 – Item 9 of the diagnostic test

Five of the eight learners (63%) selected the incorrect Option D, reasoning that the change made by light bulb B would not affect the rest of the circuit. This reflects the misconceptions related to the short circuit preconception and local sequential reasoning, as identified by Sencar and Eryilmaz (2004). When viewed through the lens of the domino effect, the rationale behind the learners' reasoning becomes apparent. It is possible that the learners reasoned that the dominoes moving toward light bulb A would continue to fall, irrespective of any changes made to light bulb B (Figure 4-37).

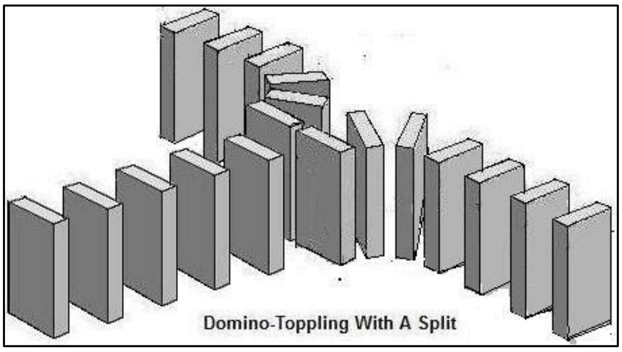


Figure 4-37 – Domino effect with a split

In explanations provided for a variety of option selections across Items 1–4 in the diagnostic test, which requires knowledge of current and voltage or both, there is evidence of a lack of distinction between these two ideas:

> *In a series circuit, voltage is constant and in a parallel circuit, the voltage is split.*
>
> *… in series, each component receives the same amount of voltage.*
>
> *This is because the voltage is decreased after the first light bulb leading to Q being dimmer and P will turn on before Q as they are in series.*

Again, while the confusion between these two concepts has been documented (Engelhardt & Beichner, 2004) and Teacher B has observed it throughout her teaching career, it is possible that her teaching strategy could be affecting this understanding as well. As presented in the worksheet, if both concepts are introduced together in the same lesson without first ensuring that each concept is well understood individually, it may be a source of confusion for learners.

4.3.4 Worksheet 3 – Resistance

Conceptual Teaching Strategies

The third worksheet that Teacher B issued to her learners was titled *Resistance*. While it focused primarily on the relationship between resistance and current in both series and parallel circuits, it also included two sections where she attempted to bring the ideas of current, voltage and resistance together. The structure of the worksheet is summarised with words below but was mostly presented in the format of circuit diagrams (See Annexure F).

Worksheet 3 addressed the following concepts:

Concept 7: Relationship between current and resistance in a series circuit

> Learners were instructed to: Construct a series circuit in the simulation with a light bulb, a cell, and an ammeter, then record battery voltage, light bulb voltage, and ammeter reading on the worksheet. Add a second light bulb and a resistor in series to the same circuit and record the same measurements on the worksheet.

Here, the learners should notice that the more resistors that are added in series, the lower the total current in the circuit, while the voltage over the cell is divided between the resistor and the light bulb, although not required to be recorded on the worksheet (Figure 4-38).

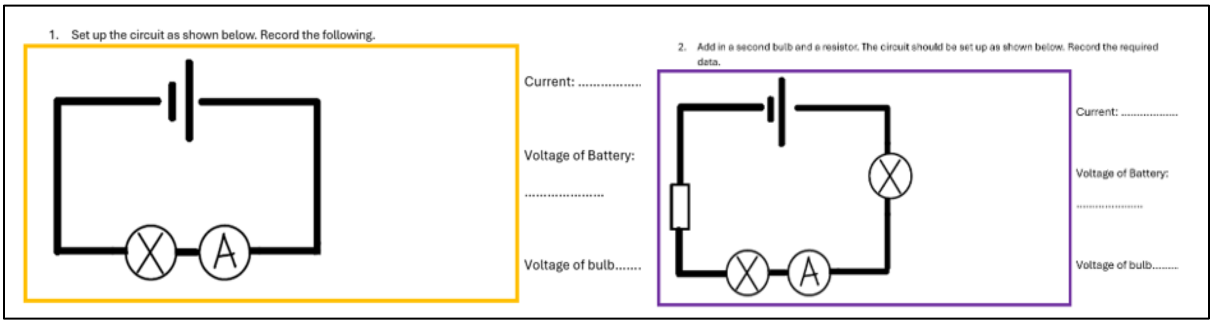


Figure 4-38 – Question 1 and 2 in Worksheet 3 of Teacher B

Concept 8: Relationship between current and resistance in a parallel circuit

> Learners received the following instructions: Construct a parallel circuit in the simulation with two light bulbs in parallel, each with an ammeter in series, and a cell with an ammeter in the main branch. Record readings from all ammeters and the voltage across each bulb and the cell the worksheet.

Figure 4-39 compares the instruction given in the worksheet with the resultant diagram built in the simulation.

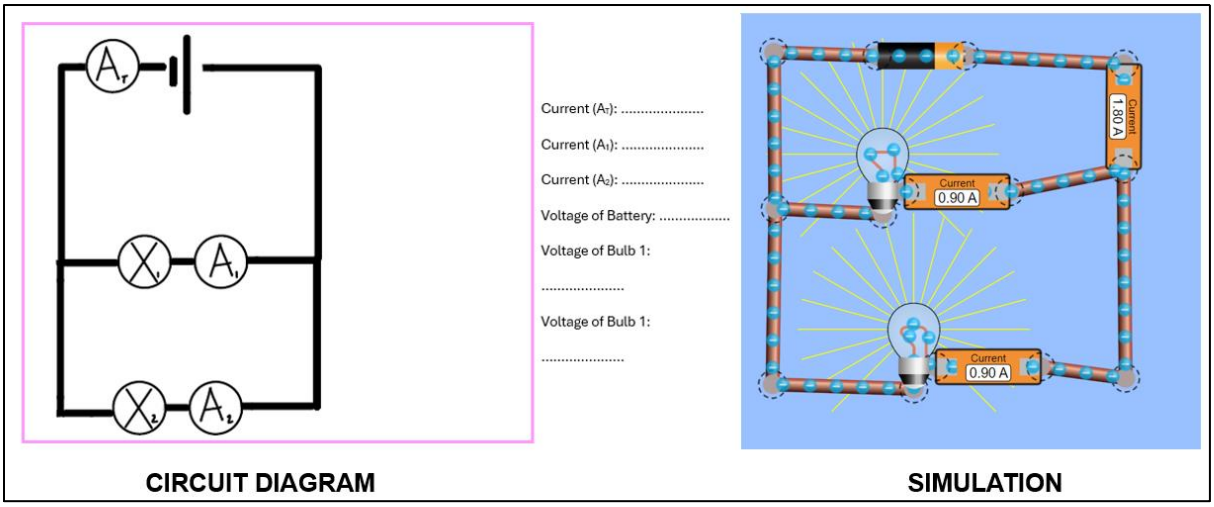


Figure 4-39 – Circuit diagram in Question 3, Worksheet 3, compared to circuit built in PhET simulation

A further instruction was to add one resistor in series with each light bulb in both parallel branches and record new readings on the three ammeters. Figure 4-40 compares the instruction given in worksheet with the resultant diagram built in the simulation.

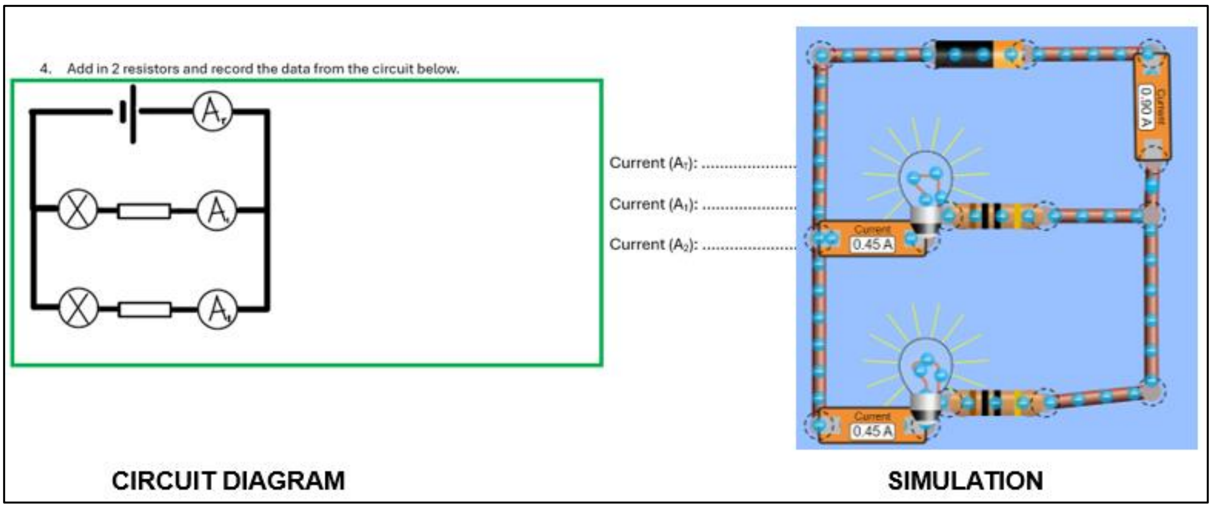


Figure 4-40 – Circuit diagram in Question 4, Worksheet 3, compared to circuit built in PhET simulation

This is where the representation could have been structured better and may have lost its direction. While Concept 7, Task 1 in Worksheet 3 (Annexure F), investigates the impact of adding more resistors in series on the total current of the circuit, Concept 8, Task 2 in Worksheet 3 (Annexure F), should sequentially investigate the effect of adding more resistors in parallel on the total current of the circuit. Instead, the change that occurs between the two circuits is an increase in the resistance of each parallel branch. While this still shows a decrease in the total current of the circuit, it still does not directly answer the question: What happens to total current when more resistors are added in parallel?

As a result, it can be seen that the teacher's PCK of CTS and representations needs development. The current representation is lacking clear direction and purpose and requires refinement to clarify the main idea and intended understanding for learners. This will support conceptual development as intended (Mazibe et al., 2020).

Concept 9: Current and voltage of resistors in series vs. current and voltage of resistors in parallel

> The teacher instructed the learner as follows: In the simulation, construct the following series circuit. Then, on your worksheet, write down the readings on the corresponding ammeters and voltmeters.

Unless Teacher B had told her learners to add a voltmeter over the resistor in this circuit, the ability of resistors in series to act as voltage dividers would not have been noticed in this circuit construction since there is no voltmeter connected over the resistor in the circuit (Figure 4-41).

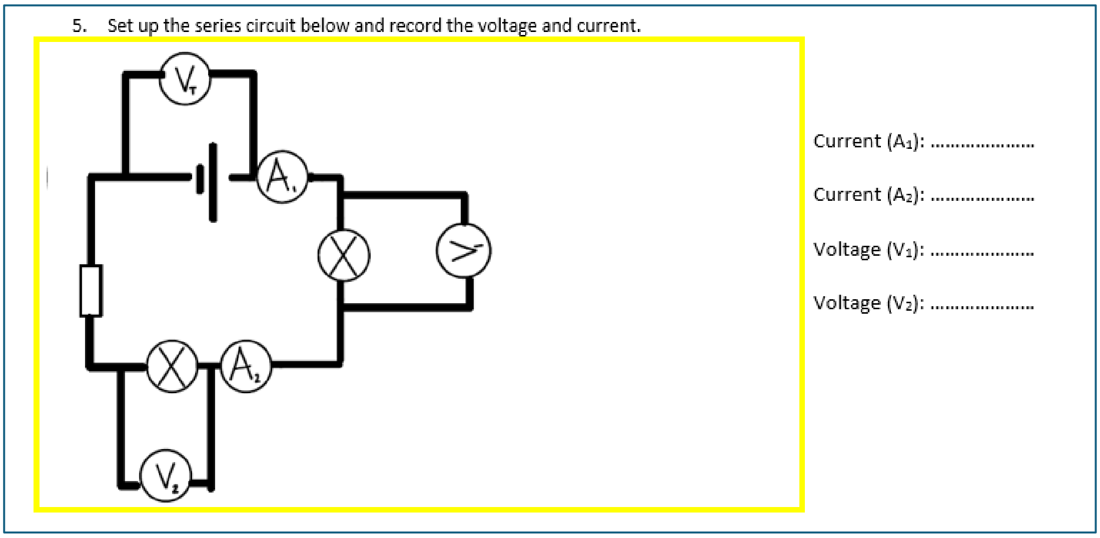


Figure 4-41 – Question 5 from Worksheet 3

> Then, in the simulation, construct the following parallel circuit. On your worksheet, write down the readings on the corresponding ammeters and voltmeters.

Question 6 in this worksheet (Figure 4-42) also presents a similar limitation. Although the voltmeters are positioned across the battery and individual light bulbs, a clear pattern will not emerge unless an additional voltmeter is added across the resistor in series with each light bulb. This omission undermines the question's purpose. Once more, learners primarily observe how current divides in a series circuit.

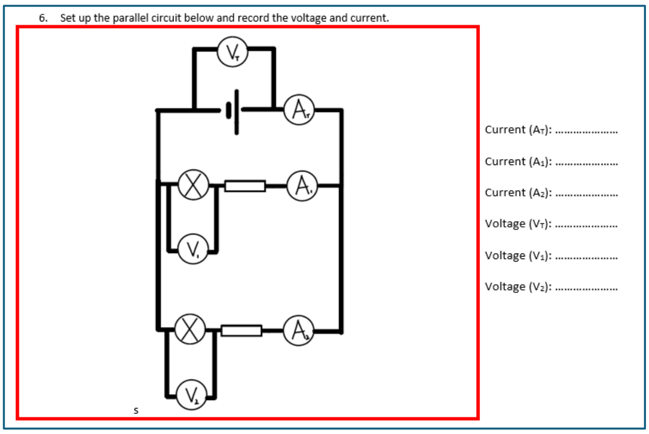


Figure 4-42 – Question 6 from Worksheet 3

It is important to acknowledge that while Teacher B mentioned that learners have consistently struggled with distinguishing between voltage and current, her worksheet provides an opportunity to address these concepts together. Analysing the worksheet from a broader perspective reveals a systematic approach: first addressing current, then addressing voltage, and finally demonstrating how these ideas interact within a circuit. This approach highlights Teacher B's high-quality PCK in illustrating the interrelation of concepts and systematically working through them, which are some important characteristics of exemplary PCK as described by Mazibe et al. (2023).

Concept 10: Using the formula $R = V / I$ to calculate current, resistance, and voltage

> Learners received the following instructions: Use the Ohm's Law representation given on your worksheet to calculate resistance, current, and voltage.

This is another attempt at giving learners an opportunity to relate the three ideas of current, voltage, and resistance together, only this time in a different format to circuit diagrams (Figure 4-43).

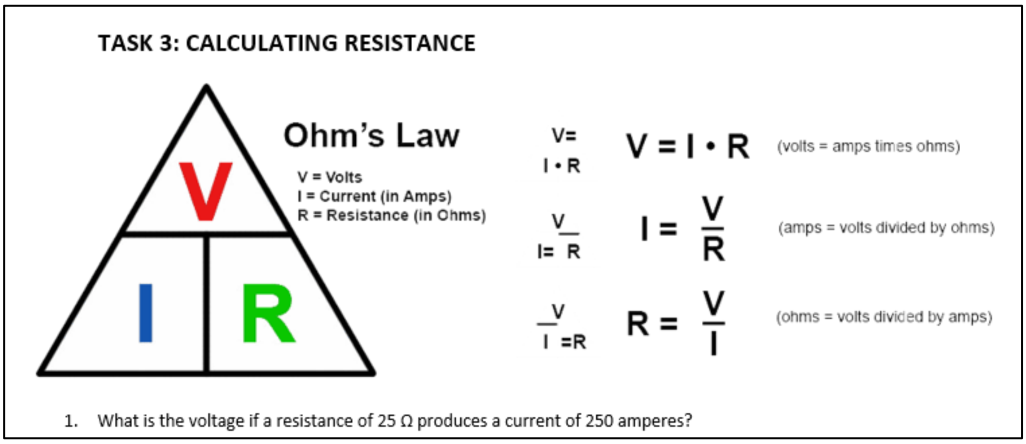


Figure 4-43 – Image 3 from Worksheet 3

During the interview, Teacher B did not specifically mention how or when she used this worksheet. However, when asked to confirm whether she covered current, voltage and resistance as concepts in both series and parallel circuits, she mentioned how it took four 50-minute lessons in total, including her taking some time to say "right, now, let's actually go through them before I give you some practice problems".

Additionally, since Worksheet 3 mostly covers the relationship between resistance and current, it is important to highlight how she also used a traffic analogy to help her learners understand this relationship:

> *What I do with circuits is I do a lot of analogies with them, so I tend to use a lot of things like traffic when I explain like resistance. I say to them: "Let's say there were three lanes and all of a sudden two of those lanes were cut off and there's a roadblock there. How does that affect the speed?" and they're like "Oh, they go slower".*

In this analogy, Teacher B explains that a higher resistance (fewer traffic lanes) means lower current (cars moving slower). This analogy has some flaws because it incorrectly equates current (coulombs per second) with speed (metres per second) and takes away from the essential idea that current is the AMOUNT of charge passing a point per second. While the analogy might help illustrate the difference in resistance between series and parallel circuits, it loses effectiveness when the purpose is not clarified. Using Mazibe, Gaigher, et al. (2020) as a guide to evaluate her PCK for this specific CTS, it is evident that her PCK is limited. This limitation arises because the concepts are explained in isolation, and their interrelations are not fully clarified.

Learner Understanding of Science

To determine how the worksheet supported the learners' conceptual reasoning and understanding, items in the diagnostic test that relate to or address some of the four main concepts outlined above are compared and analysed accordingly.

Concept 7: Relationship between current and resistance in a series circuit

The relationship between current and resistance is generally well understood by learners. When presented with items in the diagnostic test in which learners had to reflect on the relationship between resistance and current (like Item 4 and Item 7), a few responses revealed an accurate understanding of this idea:

> *The greater the resistance, the lesser the current will be. This is because the resistance is blocking electron flow, and thus, the flow of electrons; current, will be decreased.*
>
> *Resistance restricts the electrons passing through, weakening the strength of the current.*
>
> *The current would not be the same on both branches due to the higher resistance in the branch with P and Q.*

Interestingly, responses mentioning "blocking, opposition, or ease of flow" evoke the same image as Teacher B's traffic analogy for resistance and current. This suggests that some learners applied her classroom teaching in their answers.

In Item 7 of the diagnostic test, learners were asked to describe the voltage and current at different parts of the parallel circuit (Figure 4-34). While not all of the responses included the correct selection of the voltage distribution, all of them selected the option that displayed the correct relationship between current and resistance. Additionally, while their reasoning for their correct selection failed to include the voltage relationship, the resistance versus current relationship was present:

> *(i) is correct because resistance is less. (iv) is correct because it is 12 V.*
>
> *<u>Less resistance, more current</u>. Voltage is the same in parallel.*

Concept 8: Relationship between current and resistance in a parallel circuit

Item 5 of the diagnostic test (Figure 4-44) revealed some interesting findings. Of the three learners (38%) who selected the correct option (Option A), two of the three responses had an incorrect or incomplete reasoning for their selection, showing that the concept was not well understood:

> *[X is dimmest] because it has less resistors.*
>
> *X will shine the dimmest as it has the lowest resistance.*

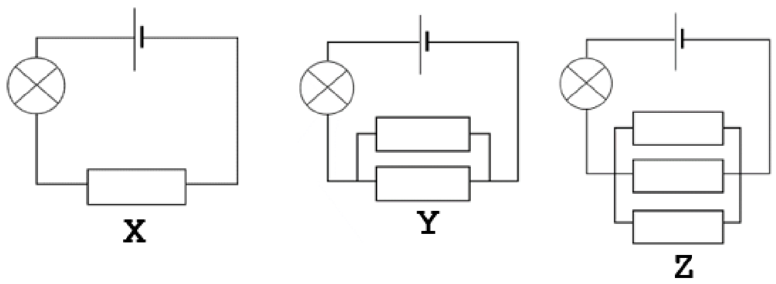
Two of the eight learners (25%) mentioned that the light bulb in circuit Z is the dimmest because the total resistance is the greatest since they have the most resistors, which reveals the parallel circuit misconception (Sencar & Eryilmaz, 2004). Finally, the remaining three learners (38%) selected Option D with the following explanation to their answers:

> *… the current is travelling anticlockwise so it moves through the light bulb first in all circuits.*
>
> *… this is because the resistors are after the light bulbs so they are all situated in the same place with regards to the power source.*

These last two responses reveal the local and sequential reasoning misconception where learners think that changes in circuits have local effects rather than effects on the whole circuit (Cohen et al., 1983). This result is similar to how some of Teacher A's learners responded to this item in the diagnostic test.

Question 5

In which circuit would the light bulb shine the dimmest?



A. Circuit X.
B. Circuit Y.
C. Circuit Z.
D. The light bulb will shine with the same brightness in all three circuits.

Figure 4-44 – Item 5 of the diagnostic test

During the interview, when prompted about how she addressed the idea of the effect that adding more resistors in parallel has on the total resistance (and hence current) in a circuit, Teacher B described how she used the analogy mentioned earlier with traffic lanes and movement of cars as “the more resistance you have the more that it will actually slow down the current”. This, however, is limited to resistors in series only.

A concept such as that seen in Item 5 was not explicitly discussed in any of her teaching according to the worksheets she provided. During the interview, she admitted that the idea of resistance decreasing the more resistors are added in parallel is a really tough concept for her learners to understand and, unknowingly, revealed a misconception that she herself holds regarding resistance of resistors in parallel:

> *So, if we looked [at] it in parallel and they had actually constructed, say something that was a parallel circuit with little resistors in parallel, they would have actually seen it wouldn’t have had any effect on it because they’re all on three different circuits.*

If something similar was discussed casually in class, since this does not appear formally on the worksheet that she issued to her learners, it would reveal a possible reason for learners selecting Option D.

Concept 10: Using the formula $R = V / I$ to calculate current, resistance and voltage

When asked in the diagnostic test to describe resistance and explain its relation to current, two learners used the equation to do this, showing that they had been exposed to and remember the use of this representation in class:

> *Resistance is an opposition force to the current measured in ohms, using V=IR, it can be rearranged to R=V/I.*
>
> *Resistance is equal to the voltage [potential difference] divided by current. It is a matter of how ‘easy’ it is for the current to flow. The higher the resistance, the lower the current if voltage remains constant.*

Conclusion

In looking at the overall structure that Teacher B used to teach electric circuits, it was clear that the worksheets that she used together with the simulation followed a logical sequence as set out below in Figure 4-45:

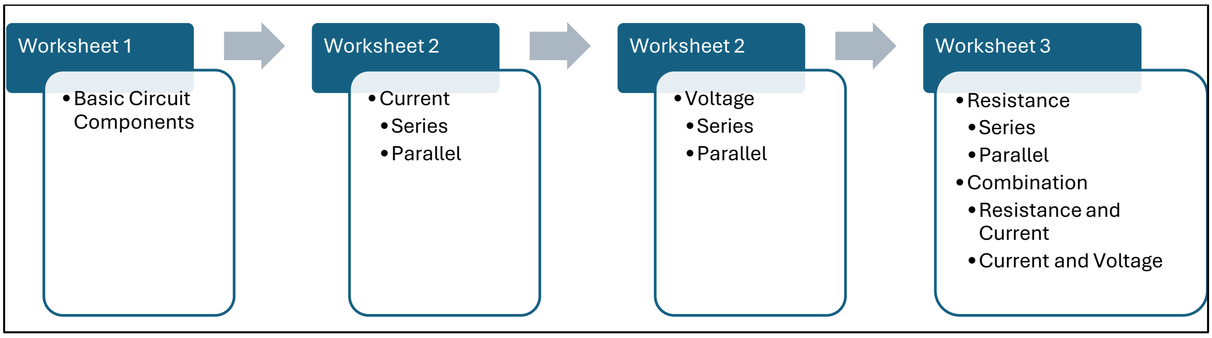


Figure 4-45 – Flow diagram showing the outline of concepts covered in all of Teacher B's worksheets

Teacher B's PCK is strong across several components, though there are areas that require further development and refinement. Her representation and worksheets with simulation created opportunities to address misconceptions and discuss difficult concepts in an inquiry-based, learner-centred environment. She was able to identify four key ideas, which were logically sequenced and interrelated, and was able to distinguish supporting subordinate ideas in these worksheets.

Regarding teacher knowledge of learner understanding of science, she identified specific challenging concepts and understood the common difficulties her learners faced. The learner results show a good general understanding of the key ideas that the teacher wanted to convey, despite some details that still need to be grasped. The freedom for each of them to explore relationships and arrive at their own conclusions had an overall positive effect on how they understand the concepts being taught.

4.4 Results of Teacher C

Teacher Description

Teacher C teaches science to learners at a private school in Collaroy, Australia. He is proficient in English and has 37 years of experience teaching high school science, with a specialisation in geology, as well as Earth and environmental science. He spent 15 years teaching in the United Kingdom and gained the remainder of his experience in the Australian education system. In this school, high school learners from Grade 7 to Grade 10 are grouped into classes based on their gender and academic performance from the previous year. In addition to other classes, Teacher C taught a class of 14 male Grade 9 learners with strong academic capabilities. The topic of electric circuits was taught to this class over a week and a half towards the end of Term 2 in 2023. The data sources for this analysis include the information gathered from the interview and the findings derived from the diagnostic test that his learners completed.

Additionally, Teacher C provided one PowerPoint presentation, which he used as the backbone to his lessons, and a set of worksheets that he issued to his learners during that time.

The following is a three-part analysis for each significant representation that Teacher C used when teaching electric circuits. These three parts, which have been presented under the two main components of teacher PCK as discussed in the conceptual framework, include knowledge of:

- **Conceptual Teaching Strategies**
  - What the representation is and how the teacher used it in class.
- **Learner Understanding of science**
  - Learner knowledge about electric circuits.
  - Whether a connection exists between the CTS used by the teacher and how the learners understand the concepts of electric circuits.

4.4.1 Representation 1: Building Circuit Boards

Conceptual Teaching Strategies

Teacher C used his PowerPoint presentation to structure and sequence his teaching of the various concepts. During the interview, he mentioned that his learners were familiar with the circuit symbols used in the diagnostic test. This was because identifying and drawing circuit symbols was among the first activities that he did with his class at the start of this topic:

> *… we had gone through the symbols that were used in the circuits in class. The kids had actually copied it down and they were provided with another eight other symbols other than those; so voltmeters, motors, all of that sort of stuff.*

Figure 4-46 displays the slide from Teacher C's presentation that his learners had to copy.

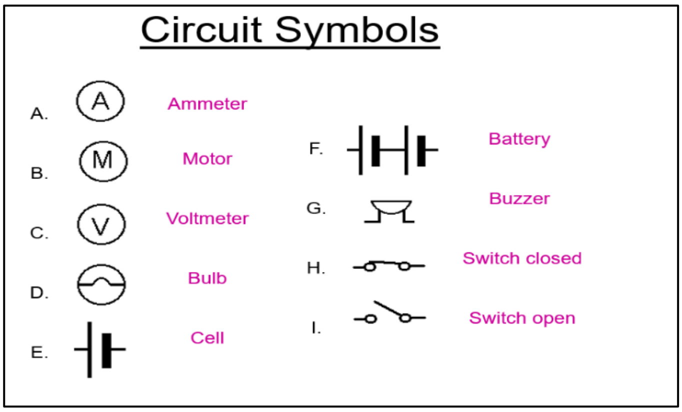


Figure 4-46 – Slide 6 of Teacher C's presentation

Thereafter, Teacher C instructed the learners to draw basic circuit diagrams using these circuit symbols by adhering to any formal rules or conventions as indicated by him. For example, during the interview, Teacher C described "the convention of putting the power source on the top". This application is shown in Figure 4-47.

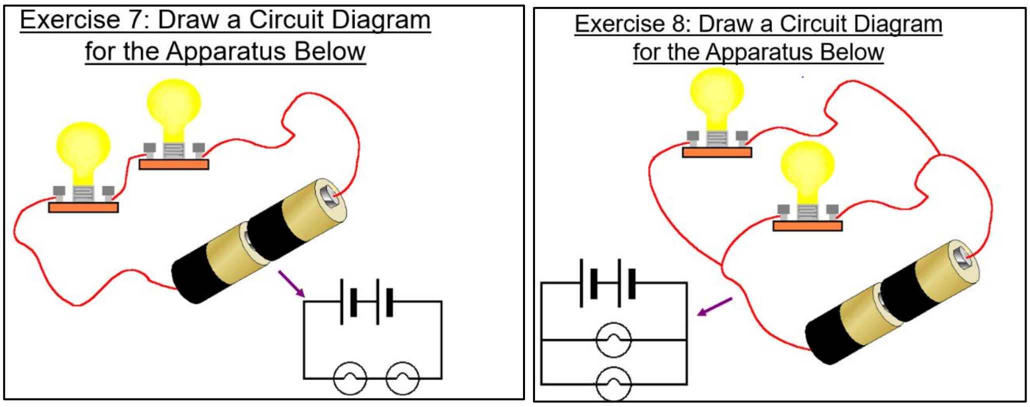


Figure 4-47 – Slide 11 and 12 from Teacher C's PowerPoint presentation

During the interview, Teacher C explained that his learners, working together in groups, spent time building circuits using physical circuit kits in the classroom. When prompted about the structure of these lessons, he described how he relied on his PowerPoint presentation to guide his learners through the various circuit connections that they needed to build with the circuit kits:

> *What we did was I actually have a slide set that I wrote when I worked in England and it goes through all of that. So, we actually look at series and parallel and short circuits and then we look at inserting the ammeters and the voltmeters and why they measure what they measure and things like that.*

Figure 4-48 shows the four different circuit investigations that Teacher C had prepared for his presentation and that guided his learners through practical activities in their groups. In response to questions about the reliability of the circuit kits, Teacher C found that circuit kits "not working" is part of learning:

> *There's no point in going: "This is rubbish! I'm throwing it away". Train the kids to say "OK, this is not working. What are the possible problems and let's fix them. Let's check them one at a time".*

Teacher C added that another common mistake while working with the circuit kits is that learners incorrectly connect the voltmeter and ammeter. In this case, he directs his learners back to their circuit diagrams to determine why their connection is incorrect:

> *And then when you go and check it, you find that they've actually got the ammeter wired in parallel and the voltmeter in series, it's just like, no, no, no, let's go back and look at the diagrams that we started with. What have you made a mistake on and try and actually coach them to actually identify their own errors.*

It is important to consider the value that can be gained from using this approach. While reading, drawing, and understanding circuit diagrams on paper is a good start, being able to make the connection between theory (on paper) and practice leads to a deeper understanding (Ferri et al., 2016). This connection is a valuable skill that Teacher C imparts to his learners as he views moments of frustration as learning opportunities. In their rubric to assess and quantify the enacted PCK of teachers for a specific topic in physics, Mazibe et al. (2023) characterised an exemplary display of PCK as a CTS that effectively engages learners by encouraging discussion, asking questions, and providing explanations throughout the lesson. Given that Teacher C employs all these methods in this activity, his PCK can be categorised as of high quality.

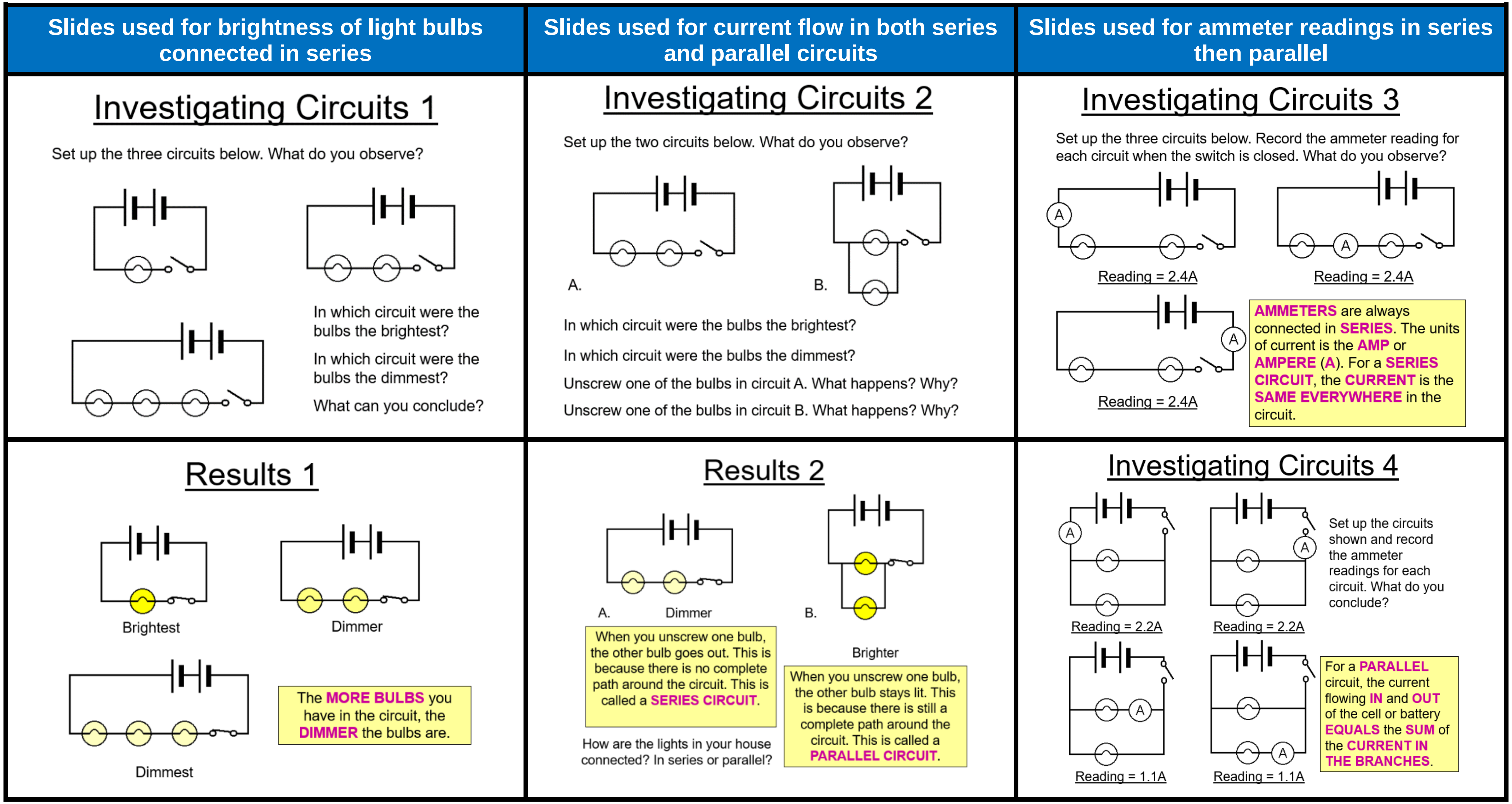


Figure 4-48 – Slides in Teacher C's presentation used to construct circuits

Learner Understanding of Science

Since the learners had no opportunity to draw circuit diagrams in the diagnostic test, and the teachers were allowed to explain the symbols given in each item, it is challenging to determine whether Teacher C's teaching approach in the first part, which covered circuit symbols and diagrams, directly influenced how his learners responded to the items in the diagnostic test.

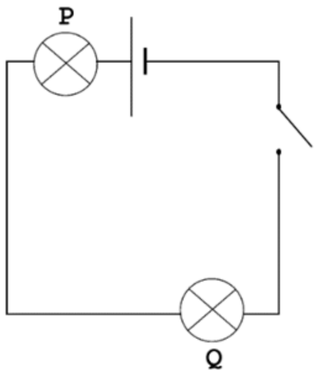
Fourteen learners in Teacher C's Grade 9 Science class completed the diagnostic test. The data used to assess the impact of this representation (circuit board practical tasks) on learners' understanding of concepts in electric circuits was sourced and analysed from their responses to specific items in the diagnostic test that are related to the four main concepts labelled as "Investigating Circuits" in Figure 4-48. It is important to note that not all these concepts were taught exclusively through circuit boards. During his interview, Teacher C mentioned using analogies to help learners grasp some key ideas in addition to the circuit-related practical tasks. Thus, a combination of hands-on circuit board activities and these analogies contributed to the learners' responses. The specific analogies are discussed later in this analysis.

Investigating Circuits, Items 2 and 3: Light bulbs shine with the same brightness when connected in series and have the same current running through the circuit

In Item 3 of the diagnostic test (Figure 4-49), 13 out of 14 learners (93%) selected the correct option (Option C).

Question 3

In the circuit below, all the bulbs are identical. Compare the brightness of the light bulbs the moment that the switch is closed.



A. P is the brightest and Q is the dimmest and P shines before Q does.

B. P is the brightest and Q is the dimmest, and both light bulbs light up at the same time.

C. P and Q have the same brightness and both light bulbs light up at the same time.

Figure 4-49 – Item 3 of the diagnostic test

The following responses correctly mention "brightness" and refer to "current being the same", which may be related to the activity in which learners recorded current using ammeter readings during their practical task.

> *Because the **current is the same**.*
>
> *The same amount of electricity will enter each bulb meaning that they will be **the same brightness,** but not a bright as just one bulb.*
>
> *It doesn't matter where they are in the circuit, they will shine **the same amount of brightness**.*

The results indicate that learners have a good understanding of current flow in a series circuit. It is worth mentioning that Teacher C approached this concept using a variety of teaching strategies. This included (1) using circuit boards to practically demonstrate the same current flow through ammeters in series; (2) using an analogy to compare current flow to that in Christmas lights (discussed later); and (3) incorporating related questions into worksheets to which learners should respond. This dynamic use of several teaching strategies associates Teacher C's PCK with that of high standards since he used a variety of representations to explain important concepts (Mazibe et al., 2023).

Only one learner selected an incorrect option (Option A) for Item 3, revealing a documented misconception, namely the weakening current misconception model (Sencar & Eryilmaz, 2004):

> *The electricity flows from the big end of the cell, so P takes up the most energy, and Q will be left with less electricity so it will shine dimmer.*

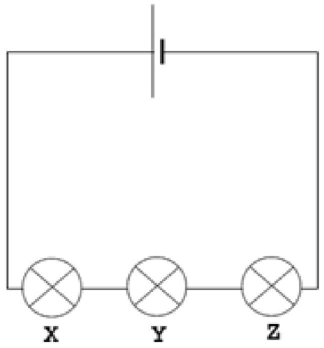
(Other explanations provided by the learners to this question are discussed later.)

Investigating Circuits, Item 2: If one of the lights in the series circuit blows out, none of them will work

The results of the responses to Item 2 of the diagnostic test (Figure 4-50) appear quite similar to those of Item 3, which was discussed earlier. Out of the 14 learners who took the test, 13 (93%) selected the correct option, while only one learner selected the incorrect option.

Question 2

Light bulb Y blows out. What will happen to the **other light bulbs** in the circuit?



A. Light bulb X and Z will continue to shine.
B. Only light bulb X will shine.
C. None of the light bulbs will shine.

Figure 4-50 – Item 2 of the diagnostic test

Out of the 13 explanations to the correct responses, nine refer to the inability of electricity to flow due to a break, hole or incomplete circuit. Another two explanations included simple, short phrases like “series circuits, not parallel”. While these explanations may not reveal sound conceptual reasoning, they may be related to how learners connected these same circuits in their practical activities.

During the interview, Teacher C mentioned how he directly addressed this specific idea in class of current no longer flowing through components in a series circuit if just one component is not working and connects this with the reason for the correct selection of options in the test:

> *We actually addressed that particular circuit in the slide set, OK, so that’s probably why the results are so good on that.*

Finally, the explanation provided for the incorrect option selected (Option A) revealed an interesting result:

> *Because the light bulb still completes the circuit, and now is just a resistor.*

So, this learner does not understand the connection between a blown light bulb and a break in the circuit. Instead, the learner sees the light bulb simply take on another role, possibly because the light is still connected to other components in the circuit. (This was not the same (only) learner that selected the incorrect option in Item 3 of the diagnostic test.)

Investigating Circuits, Items 7: Current is divided in a parallel circuit

In Item 7 of the diagnostic test (Figure 4-51), only seven of the 14 learners (50%) selected the correct option (Option D). Despite this, none of the explanations provided for this item are entirely complete or correct. We turn our attention to the only explanation provided by one of the learners who selected the correct option that mentions both voltage and current:

The current is affected by the resistor, but the voltage is not.

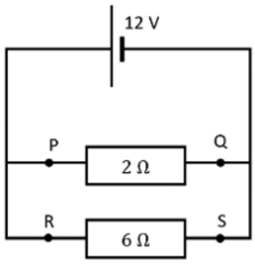
Although the learner did not explain why the voltage remains unaffected by the resistors (which is not entirely accurate), they did correctly apply the rules of circuit analysis. This is evident as the voltage remains the same across each branch.

Other explanations provided for this question focus more on current and resistance and mention voltage less frequently. Three learners did not provide any explanations, with one learner explicitly stating:

I don't really know. I'm guessing. I don't exactly understand the question.

Question 7

Read the five statements below, describing current and voltage in the circuit.



i. *The current between points P and Q is greater than the current between points R and S.*
ii. *The current between points P and Q and points R and S is the same.*
iii. *The voltage between points P and Q and points R and S is both 6 V.*
iv. *The voltage between points P and Q and points R and S is both 12 V.*
v. *The voltage between points P and Q is smaller than the voltage between points R and S.*

Which of the statement/s is/are correct?

A. Only ii and iii are correct.
B. Only ii and iv are correct.
C. Only i and v are correct.
D. Only i and iv are correct.

Figure 4-51 – Item 7 of the diagnostic test

During the interview, Teacher C mentioned using an analogy to help learners understand the role that voltage plays in a circuit, which will be discussed later. He explained that, using circuit boards, they looked at "inserting the ammeters and the voltmeters and why they measure what they measure and things like that". The only evidence that learners engaged with ideas of voltage distribution through different circuit connections is presented in the interview (where Teacher C mentioned how the learners connected voltmeters and took measurements) and in the worksheet provided by Teacher C. The same cannot be said for the current distribution since there is evidence in the interview that this was thoroughly investigated using circuit boards, discussed with the class (as per the PowerPoint presentation), and emphasised through the worksheet that Teacher C later provided. As a result, because the concept of current was given more teaching time than that of voltage, it is understandable why learners lack a thorough understanding of voltage distribution and provide incorrect explanations or completely avoid explaining related ideas.

4.4.2 Representation 2: The Water Pump Analogy

Conceptual Teaching Strategies

During the interview, Teacher C reflected on his teaching strategy and mentioned that he had his learners physically construct different circuit connections using circuit boards. After this activity, he described the concepts of current, voltage and resistance by using an analogy:

> *I actually use the water pump analogy where voltage is the water pump pushing the water through. A resistance is where you actually go from a fatter hose to a thinner hose and that sort of thing, and the amperage is simply just the flow rate.*

Teacher C extended the analogy and explained how this analogy relates all three concepts together:

> *I use the idea of stiffening your thumb over the end of a hose because you're constricting it to actually maintain the same flow rate of volume through the hose because you've got a constrictor on the end. It's got to move faster through the constriction point, and that pushes the water to go further, so it gets a greater velocity.*

Before the use of this representation is investigated any further, it is important to acknowledge three limitations of the analogy. Voltage is compared to a water pump pushing water through the circuit, resistance to that which affects water flow (like the thickness of the hosepipe or the stiffening of your thumb over the end of the hose), and current to the rate at which water flows through the pipe.

Firstly, in this analogy, it is the water pump, as the sole source, that determines the rate of water flow through the hosepipe. If the water pump is made analogous to batteries, the analogy breaks down. Learners could believe that the same flow rate will result regardless of the number of batteries (since they all still function as a water pump) and the number of resistors in the circuit.

Secondly, the number of restrictions in the hosepipe does not affect the flow rate of water through the hosepipe, as this is determined by the water pump. If this situation is made analogous to resistors in an electric circuit, then the number of resistors connected in series would not have any effect on the current. Although it is true that partially covering a water hose's opening can increase the speed of the output water in real life, the amount of water flowing remains the same. While this statement is not entirely incorrect for resistors in electric circuits (the drift speed of electrons through resistors may be slightly faster), it could potentially cause confusion for learners in the future. Here, if learners view current as the speed of water flowing through a hosepipe, then adding one resistor to a series circuit would increase the overall current, contrary to what happens when total resistance is increased in a series circuit.

Finally, this resistance concept would not apply to resistors connected in parallel either. While Teacher C's analogy may serve as a valuable representation to help learners visualise the overall role that resistance, current and voltage play in different circuit connections, caution should be taken to ensure that learners understand how a change in one of these variables affects another differently in the various circuit connections.

This reveals that Teacher C may have a limited PCK regarding the effective use of such a representation on learner understanding. Instead of addressing misconceptions about electric circuits, the representation could potentially create new ones. This concern has frequently been highlighted by various authors (Aligo et al., 2021; Moodley & Gaigher, 2019; Preston, 2019).

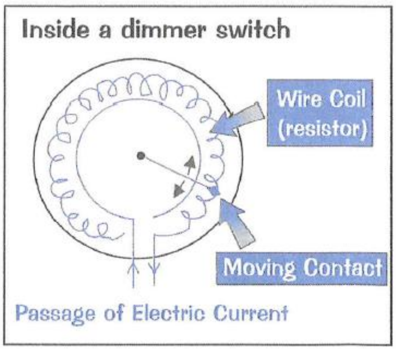
Teacher C's main reason for using this particular analogy is "just so that the learners get the idea of what's moving through the circuit". During the interview, he acknowledged other analogies, but based on his experience, he has found that learners understand this is particular analogy well. Additionally, he reiterated that many ideas in electricity should be kept as simple as possible.

Again, while there is value in using analogies to help make abstract concepts, like those in electric circuits, more accessible and easier to understand, there is a risk in the analogy leading to further confusion if the limitations are not clearly stated and discussed with learners. It seems that Teacher C was not able to identity the limitations of this analogy despite good intentions.

The worksheet that Teacher C provided did not allow learners the opportunity to write down their own version of the definition of current, voltage and resistance. However, there were many opportunities for learners to investigate the relationship between **current** and **resistance**. For example, Figure 4-52 shows a question from the worksheet that addressed the relationship between **current** and **resistance**:

Q3 *A dimmer switch controls the brightness of a light: turn it clockwise to increase the brightness, or anti-clockwise to decrease it. It works by using a variable resistor to control the current in the bulb.*

— It is illustrated in the diagram opposite.



a) Draw the path followed by the current if the lights are **dim**; **medium brightness**; and **bright**.

Below are three readings of current and resistance taken from the switch at different settings.

b) Complete the table using the same descriptions for brightness used in part **a)**.

c) What happens to the size of the current when the resistance is increased?

d) What happens to the size of the current when the resistance is decreased?

Brightness of Lights	Current(A)	Resistance(Ω)
	1.0	6.0
	2.0	3.0
	3.0	2.0

Figure 4-52 – Question 3 from Teacher C's worksheet

Figure 4-53 shows a flow chart that is used to represent the sequence of concepts addressed while teaching. There is a possibility of an intermediate connection not being explicitly explained in these concepts.

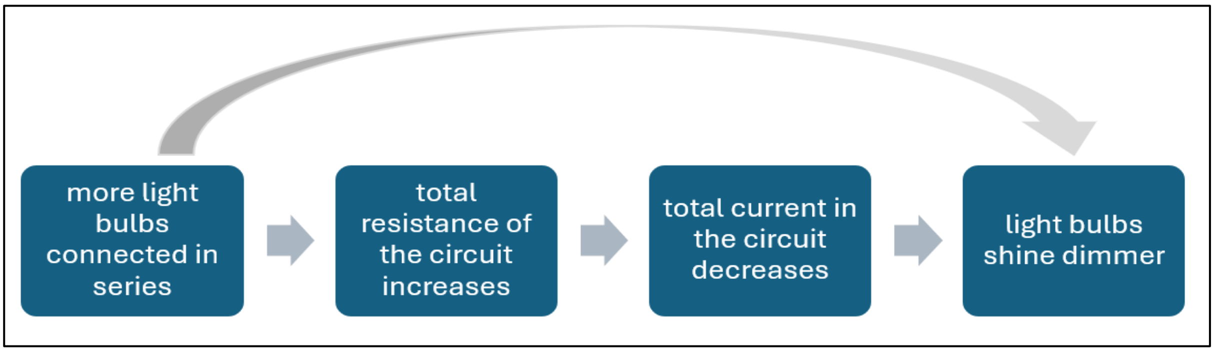
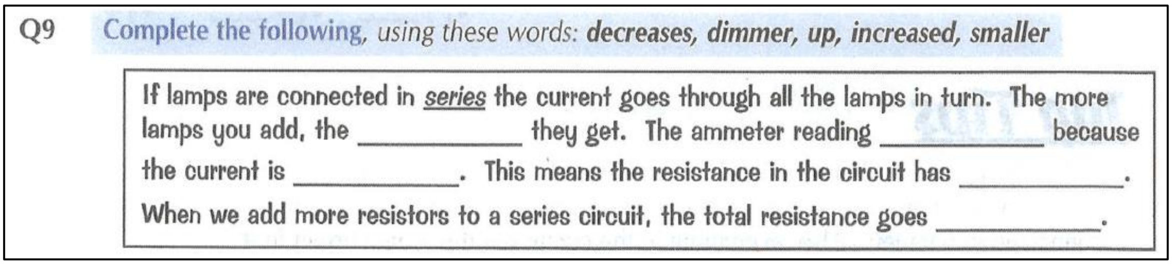


Figure 4-53 – Flow chart showing the logical sequence of thinking from resistance to current

The PowerPoint makes a connection between the number of light bulbs connected in series and the brightness of the light bulbs (refer to Figure 4-48). The intermediate connection, which aids in explaining WHY the light bulbs shine dimmer, is not directly addressed. While the teacher may have explained the relationship verbally in class, the omission of these intermediate ideas from the PowerPoint presentation indicates a missed opportunity to ensure the learners' conceptual understanding. By incorporating these small, yet significant connections along with the main concepts, learners may be able to better explain the reasoning behind why things happen.

Mazibe et al. (2023) describe characteristics of basic PCK regarding CTS as those that lack full explanations. This why Teachers C's PCK, based on just this activity, is considered rather limited, if he is unable to select and connect big ideas through smaller ones. The only evidenced opportunity that the learners have been given to connect these ideas can be seen in the cloze passage that comes from the worksheet issued to the learners (Figure 4-54):


Q9 Complete the following, using these words: ***decreases, dimmer, up, increased, smaller***

If lamps are connected in *series* the current goes through all the lamps in turn. The more lamps you add, the ____________ they get. The ammeter reading ____________ because the current is ____________. This means the resistance in the circuit has ____________. When we add more resistors to a series circuit, the total resistance goes ____________.

Figure 4-54 – Current and resistance relationship from the worksheet

Learner Understanding of Science

To assess if a connection exists between the analogies that Teacher C used in his teaching of the ideas of current, voltage and resistance, all explanations to all diagnostic test items were analysed to determine if any analogies used or related to ideas of "force, push or pressure" to represent voltage, “flow” or “flow rate” to represent current, and “restriction or opposition” to represent resistance as described in the analogy.

Voltage

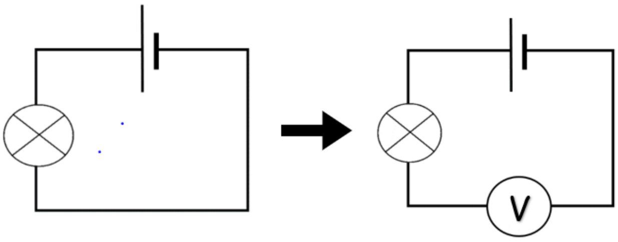
Only one learner described voltage as a means of a force or something that provides a force (in the form of a push) that sends charges flowing through a circuit. This learner incorrectly mentioned the “push” idea in Item 11 of the diagnostic test (Figure 4-55), where learners are asked to evaluate the effect of connecting a voltmeter in series to a light bulb on the brightness of the bulb:

> *… the higher the voltage, the more push there is in the circuit.*

It is possible that this learner is confusing the voltmeter with the role of the cell as a source of energy. None of the explanations the learners provided in the diagnostic test, for any question related to voltage, addressed voltage as a force, push or pressure.

Question 11

A voltmeter is connected in series to the circuit below.



What effect will this have on the brightness of the light bulb?

A. Increase.
B. Decrease.
C. Remain the same.
D. The light bulb will no longer shine.

Figure 4-55 – Item 11 of the diagnostic test

Current

Current as a “flow of charges” or “flow of electricity” is mentioned up to ten times in all the responses that require an explanation related to current. This is especially evident in Item 2, Item 3 and Item 4, as previously described in the analysis above.

Resistance

Resistance as a phenomenon that "opposes", "constricts", or "resists" the flow of current or charge is only partially mentioned in one response to Item 5 of the diagnostic test:

> *All light bulbs will shine with the same brightness because even though the current is resisted, the same amount of current still passes through the bulb.*

Based on these few explanations provided, with little reference to terms used in the analogy, there is not sufficient evidence to suggest that the analogy as a representation influenced the way that learners understood the ideas of current, voltage, and resistance.

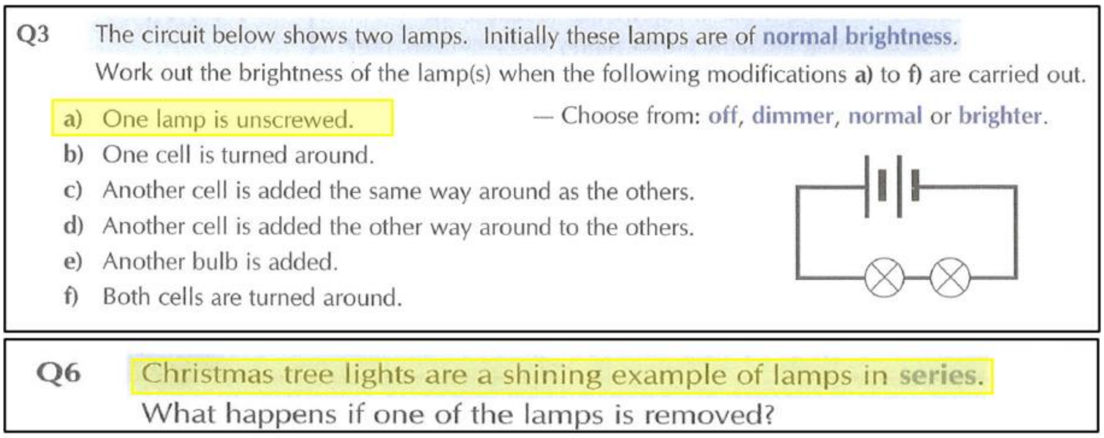
4.4.3 Representation 3: Christmas Lights Analogy

Conceptual Teaching Strategies

During the interview, Teacher C discussed Item 2 from the diagnostic test, which focused on the effect on the rest of the circuit if one of the light bulbs blows out. He described his use of a string of Christmas lights to explain current flow through series circuits and added that this is the easiest and probably one of the only practical examples of series circuits that learners will encounter in their everyday lives:

> *Well, we actually used the analogy with this as Christmas lights … which is usually about the only series circuits that most kids come into contact with. Because everything else is in parallel.*

In the worksheet provided by Teacher C, two questions (Figure 4-56) offer learners opportunities to explore the concept of current flow in a closed circuit.



Q3 The circuit below shows two lamps. Initially these lamps are of normal brightness.
Work out the brightness of the lamp(s) when the following modifications **a)** to **f)** are carried out.

a) One lamp is unscrewed. — Choose from: off, dimmer, normal or brighter.
b) One cell is turned around.
c) Another cell is added the same way around as the others.
d) Another cell is added the other way around to the others.
e) Another bulb is added.
f) Both cells are turned around.

Q6 Christmas tree lights are a shining example of lamps in series.
What happens if one of the lamps is removed?

Figure 4-56 – Questions 3 and 6 on Teacher C's worksheet

Teacher C addressed complete and incomplete circuits in another slide in his PowerPoint presentation (Figure 4-57) where learners had to build a circuit using their circuit kits. Although the analogy makes no reference to voltage distribution in a series circuit, it is still worth discussing. The analogy involves series circuits and Teacher C uses no other representation for this idea. The PowerPoint presentation present opportunities for learners to investigate the distribution of current in both a series and a parallel circuit, but nothing is said about voltage distribution for either of them.

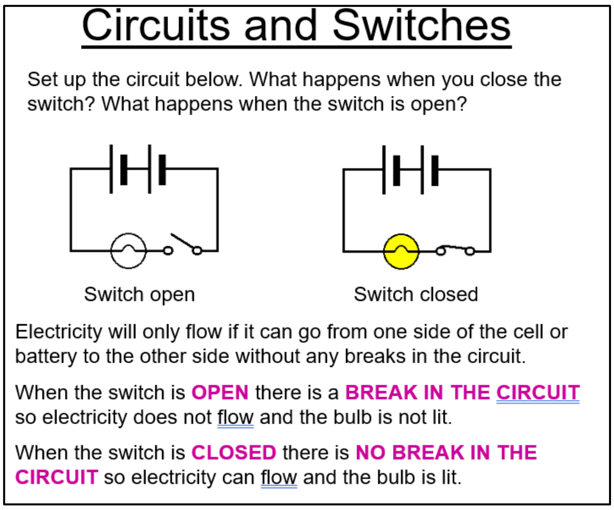
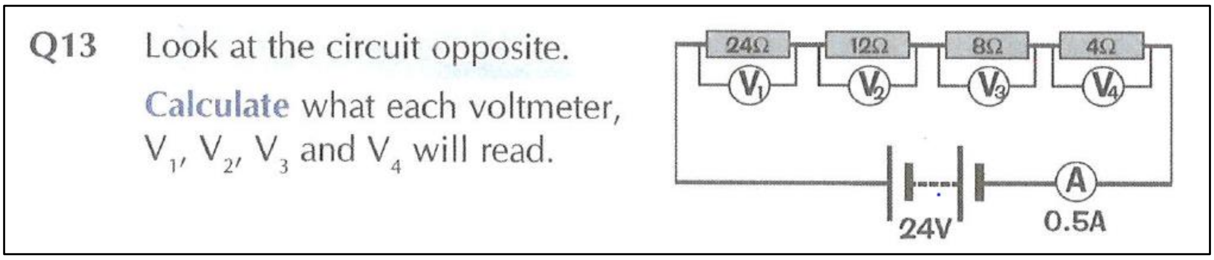


Figure 4-57 – Slide of Teacher C's PowerPoint presentation

In the worksheet, learners are asked to interact with this idea only once (Figure 4-58):



Q13 Look at the circuit opposite. Calculate what each voltmeter, V_1, V_2, V_3 and V_4 will read.

Figure 4-58 – Question in the worksheet about voltage distribution across components in a series circuit

Learner Understanding of Science

As mentioned previously in this analysis, learners answered Item 2 of the diagnostic test (Figure 4-50) assessing learner understanding of how a blown light bulb can affect current flow in a closed, series circuit) quite well, with 93% (13 of 14 learners) of the learners selecting the correct option.

A similar result (93% correct) was seen in Item 3 of the diagnostic test (Figure 4-49) where learners were asked to compare the brightness of light bulbs connected in different positions in a closed, series circuit). Of these 13 responses provided for the selection of the correct option, three used the phrase: "break in the circuit;" exactly as displayed in slide 13 of Teacher C's PowerPoint presentation. Now, earlier in the analysis of this item, attention was given to the correct responses that the learners provided and their connection to the use of the circuit board representation. However, of the 13 responses provided for the selection of the correct option, three interestingly cited voltage as the reason for the same brightness:

> *They are on the same circuit and the same current and voltage.*
>
> *They receive the same voltage.*
>
> *As the voltage is the same all round.*

Additionally, four of the reasons provided made mention of energy and how this energy is equally shared between the light bulbs:

> *They both receive the same amount of energy.*
>
> *The electrical energy is shared throughout the circuit.*
>
> *The same amount of energy passes through each light bulb.*
>
> *The same amount of energy passes through the circuit.*

These explanations are interesting because there is little evidence that Teacher C mentioned voltage as an energy concept in the interview or his PowerPoint presentation, except for the analogy of force providing energy. Since the worksheet is the only known source of exposure to voltage distribution that the researcher is aware of, learners therefore only encounter these ideas through the worksheet or class discussions. This lack of formal instruction on voltage in the PowerPoint or through the use of another representation, may explain why learners have not distinguished between voltage and current, often reasoning with them synonymously. For example, in the four reasons mentioned above, the underlined term "energy" appears to be used interchangeably with "current" and can be made accurate by simply replacing "energy" with "current" in each instance.

4.4.4 Representation 4: Classroom Light Connection

Conceptual Teaching Strategies

In an attempt to explain the main feature of parallel circuits, Teacher C described how he used a practical example of the actual lights in his classroom to represent how current flows through a series circuit. He found that his learners were quite comfortable with that idea:

> *In the classroom we were in, we could actually prove this because there was a light globe out and so the others were working. And I said: "Well, you know, if you've got one globe that's non-functional and everything else is working, what does that tell you what sort of circuit it is?" And they all said parallel. So, you know, they actually understand that step.*

This idea is expressed in his PowerPoint presentation (Figure 4-59):

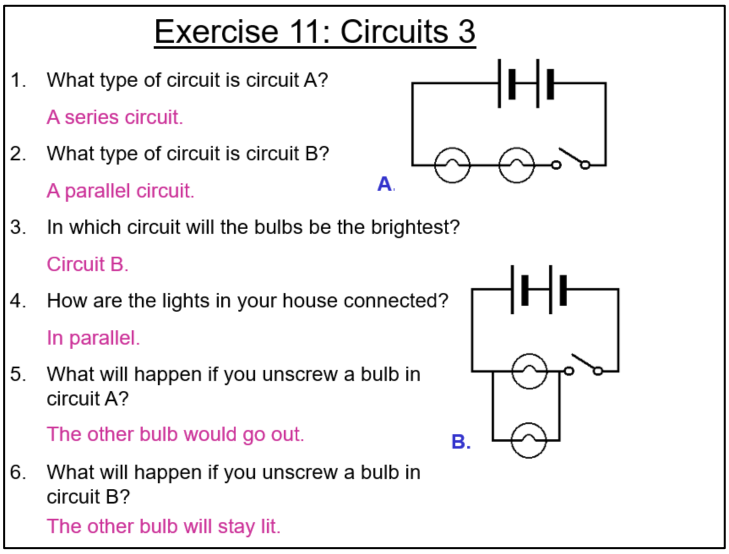


Figure 4-59 – Slide 26 of Teacher C's PowerPoint presentation.

The idea was expressed in his worksheet as well (Figure 4-60):

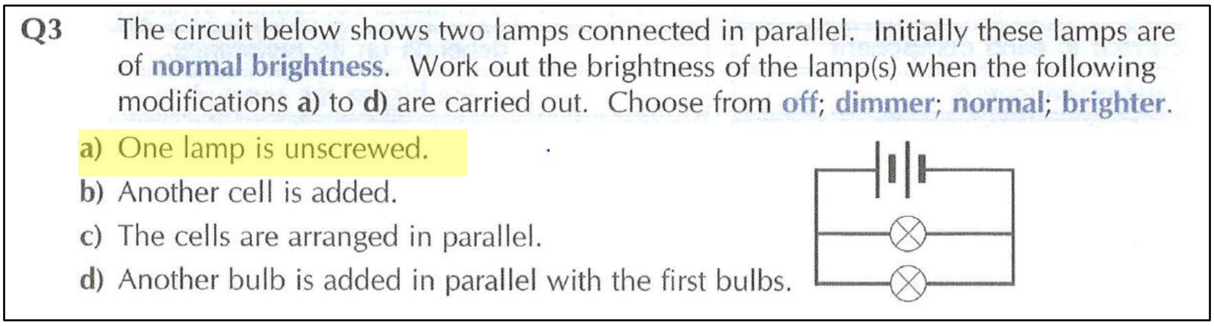
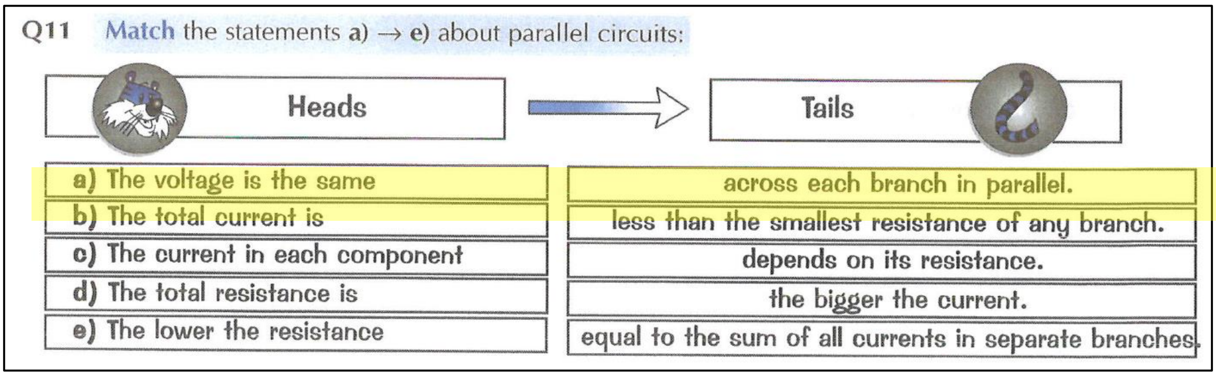


Figure 4-60 – Question 3 of the worksheet issued by Teacher C

In his PowerPoint presentation, it is clear that he addresses the idea of how current is distributed throughout the parallel circuit (Figure 4-48) when the learners had to build these circuits and connect ammeters. This is also done in the worksheet. The PowerPoint presentation, however, does not address how voltage is distributed in a parallel circuit. Additionally, there is only one very small part of a question in the worksheet that addresses voltage distribution in a parallel circuit (Figure 4-61).



Q11 Match the statements a) → e) about parallel circuits:

Heads	Tails
a) The voltage is the same	across each branch in parallel.
b) The total current is	less than the smallest resistance of any branch.
c) The current in each component	depends on its resistance.
d) The total resistance is	the bigger the current.
e) The lower the resistance	equal to the sum of all currents in separate branches.

Figure 4-61 – Question 11 of the worksheet that mentions voltage distribution in parallel branches

Furthermore, the worksheet includes a question that encourages the learners to interact with the idea of current being divided between the branches in a parallel circuit (Figure 4-62). Since this concept was addressed in one of the practical tasks during class, this question provides an opportunity for learners to reinforce their understanding of the concept taught in class.

Q12 a) Look at the diagram opposite and complete the following:
Use these words: less, branch, parallel, A_2 and A_3, more, A_1

If lamps are connected in ______________, the current in the main part of the circuit splits up and goes through each ______________.
The brightness of the lamps stays the same the ________ lamps you add in ______________.
The ammeter reading at ______________ is lower than at (A) but is the same as those at ______________.
The total resistance of lamps in parallel is ______________ than the resistance of any of the individual lamps.

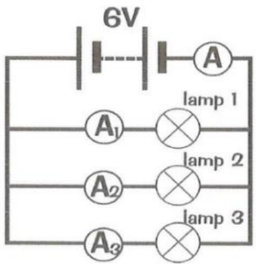


Figure 4-62 – Question 12 of the worksheet that mentions current distribution in parallel branches

As previously seen in the analysis of Item 7 in the diagnostic test, most learners understand that current in a parallel circuit divides and, even more so, that it divides according to the resistance in each branch. This idea was addressed in three different circumstances: (1) through the use of circuit kits; (2) an analogy; and (3) in the worksheet.

What learners find more challenging is how connecting resistors in parallel affects the overall resistance of the circuit. When prompted about whether he taught this idea, Teacher C explained during the interview:

> *I did … I've coloured the globes so that they're actually the three in series. The first one is brighter, the second one is a little bit lighter yellow, and the third one is a very pale yellow and they struggled with that as an idea that (if) it's the same push around, why aren't they all the same? I said, "What happens to the light globe when it's been on for 5 minutes?" and one of them went "Oh, it's hot!" And I said: "So*

what are we doing with the electricity?" and one of them went (Snap) "You're converting it into heat and light".

Figure 4-63 displays the slide that Teacher C is referring to:

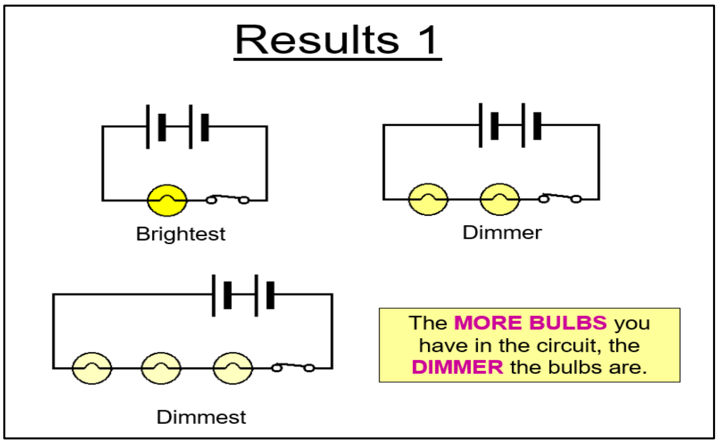


Figure 4-63 – Slide in Teacher C's PowerPoint presentation

It is worth noting that Teacher C did not directly answer the question. When asked about the effect of connecting resistors in parallel the overall resistance of the circuit, Teacher C instead referred to his lesson on connecting resistors in series. However, during the interview, he added how with some help, learners might be able to grasp such difficult ideas:

So, a lot of them were not able to intuitively pick it, but they were able to actually work it out once somebody had given them the prompt – Rather than me give it to them, I try and get them to come up with the idea.

Teacher C's technique in addressing these difficult concepts is commendable. Although there is no evidence in the PowerPoint presentation that he explicitly taught the idea that resistance decreases as more resistors are added in parallel, it is clear that he prefers his learners to use their existing knowledge, along with guidance provided only as needed, to think through challenging concepts and apply what they already know to new ideas. This approach demonstrates quality PCK. As a CTS, it is highly learner centred and supports learner thinking by providing learners with an opportunity to reveal their own misconceptions and difficulties (Mazibe et al., 2023).

Learner Understanding of Science

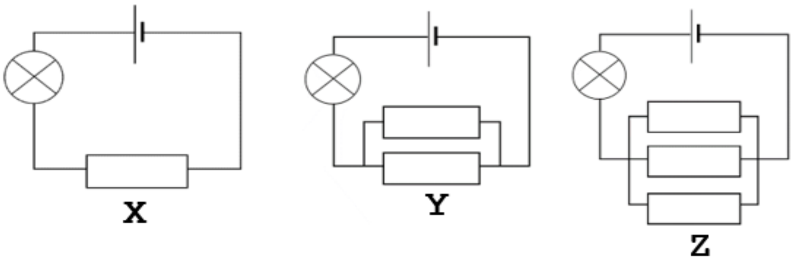
The explanations to selected items in the diagnostic test were used to assess the learners' understanding of specific concepts taught about current and voltage distribution in parallel circuits. According to the results of Item 5 in the diagnostic test (Figure 4-64), the idea that the more resistors are connected in parallel, the lower the total resistance will be, was something that the learners struggled to understand. Only one learner selected the correct option (Option A) but provided an incorrect explanation:

> *Circuit X has the least amount of resistors which means it gets the most energy, therefore it will shine the brightest.*

The 13 incorrect responses are especially interesting at this stage. Three of the 13 learners (21%) selected Option C, revealing a documented parallel circuit misconception (Sencar & Eryilmaz, 2004). All of the explanations to their answers included the idea that adding more resistors (regardless of connection type) means more resistance.

Question 5

In which circuit would the light bulb shine the dimmest?



A. Circuit X.
B. Circuit Y.
C. Circuit Z.
D. The light bulb will shine with the same brightness in all three circuits.

Figure 4-64 – Item 5 of the diagnostic test

The remaining 10 learners (72%) selected Option D. Upon analysing the explanations that accompanied their selection, it was possible to categorise the explanations into two emerging themes:

1. The light bulb will shine with the same brightness in all three circuits because the same amount of current will flow through it. What happens before or after the bulb does not affect its brightness. Two responses include:

   The resistors don't make a difference; the light bulb receives electricity first.
   [This is an indication of the local and sequential reasoning misconception (Sencar & Eryilmaz, 2004).]

   Light bulb will shine with the same brightness because even though the current is resisted, the same amount of current still passes through the bulb.

2. The same amount of current will flow through the light bulb, causing it to shine with the same brightness in all three circuits. Regardless of how many resistors are connected in parallel, the charges will always flow through only one resistor before reaching the light bulb. Therefore, there has been no change in the path taken by the electrons. To the learners, this is seen as the ability of the electrons to “choose the path of least resistance”. Some of the remaining eight responses include:

   Because it takes the easiest route, and for that to be accomplished it has to go through one, and only one.

   The electricity will flow through one single resistor in all circuit diagrams.

   As the voltage every time has to travel through one resistor.
   (More evidence of learners using current and voltage synonymously.)

   Because the electrons take the shortest route for all.

During his interview, Teacher C justified why his learners used short circuits in their reasonings “because we had just done short circuits.” They used an analogy to describe the path of least resistance idea for short circuits.

> *And we said this is why you get electrocuted and I said: “What are you made of?” And they went: “Water!” and I said: “No, not just water. What is mixed with the water?” And again, one of them said: “Oh, it’s chemicals in your body”. And I said yes, and many of those will bring up electricity. So, you form the path of least resistance.*

Now, in this response Teacher C describes a moment in his teaching when he felt he successfully helped learners understand the application of the “path of least resistance idea” in everyday situations, beyond just electric circuits. And while it may be true that in that moment learners seemed to grasp the idea, when it came to applying the concept in the diagnostic test, they were not as successful and ended up applying it in situations where it was not applicable.

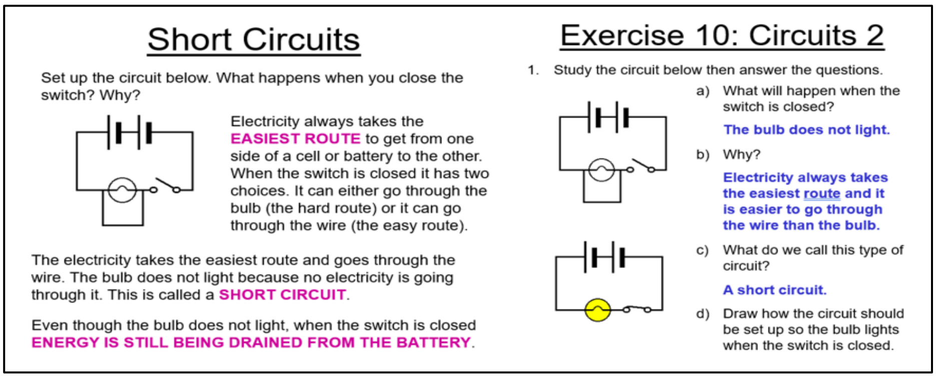


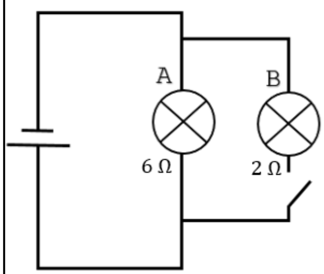
Figure 4-65 – Two slides in Teacher C's PowerPoint presentation that mention short

This is made clearer in Item 9 of the diagnostic test (Figure 4-66), an item that explicitly addressed the idea of short circuits. Only four out of the 14 (28%) learners selected the correct option with all of the explanations including a phrase with "shortest" or "easiest route", using the same phrases that Teacher C used in his PowerPoint.

Six out of the 14 learners selected Option D, indicating the misconception known as the short circuit preconception model (Sencar & Eryilmaz, 2004), where learners believe that wire connections without devices in the circuit are irrelevant and can be ignored.

Question 9

Consider the circuit below, with two bulbs A and B with resistances as indicated in the diagram. Select the statement below that is true.



A. When the switch is closed, light bulb A will not shine.
B. If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would no longer shine.
C. If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would still shine but slightly dimmer.
D. If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would still shine with the same brightness.

Figure 4-66 – Item 9 of the diagnostic test

In summary, the results indicate that learners do not fully understand the effect of short circuits on components in electric circuits. They failed to apply this concept explicitly in Item 9 of the diagnostic test and used it incorrectly when reasoning about resistors connected in parallel in Item 5. As discussed earlier, Teacher C mentioned in his interview that he encourages intuitive learning for complex concepts such as addressed by Item 5, but the results suggest that explicit teaching might have been more effective. Here, he may need to develop his PCK by selecting teaching strategies that appropriately support conceptual understanding, using powerful representations to accurately explain difficult concepts (Mazibe et al., 2023).

Conclusion

When examining the overall structure and sequencing of ideas that Teacher C used to teach electric circuits, it was apparent that the main ideas he emphasised were current flow through series and parallel circuit connections (Figure 4-67) as evidenced by the PowerPoint presentation. Voltage distribution and total resistance in series and parallel circuits were regarded as subordinate ideas that were addressed in the worksheet but not taught with the same level of significance as current.

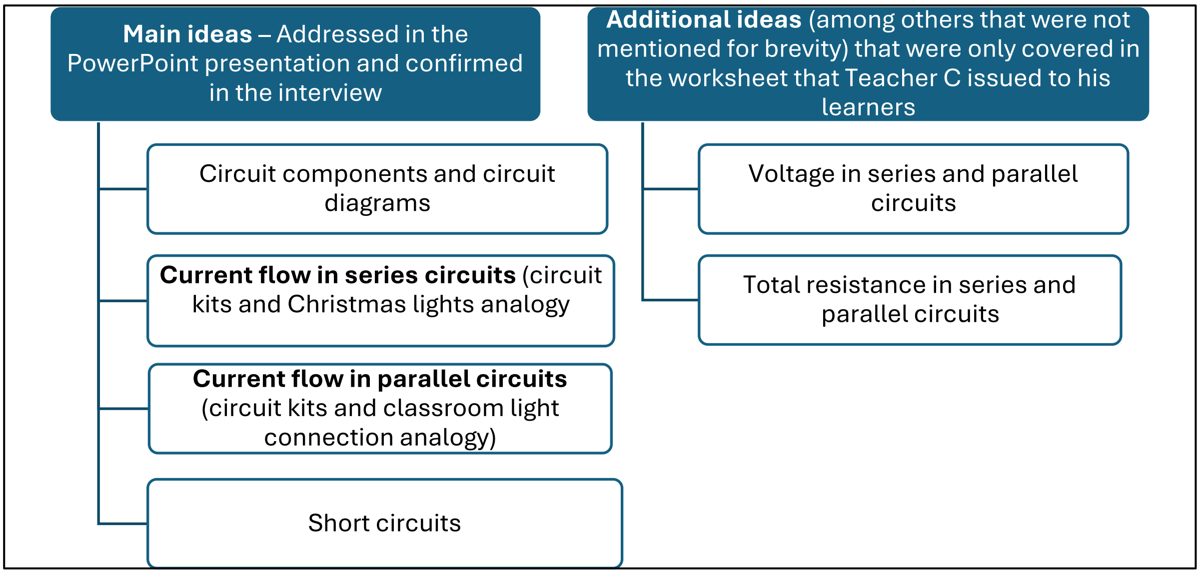


Figure 4-67 – Flow diagram showing the outline of the concepts covered in Teacher C's two main resources: PowerPoint presentation and worksheet

Teacher C's PCK is commendable for several reasons. He engages learners by encouraging them to think critically about their learning instead of immediately offering assistance during moments of struggle, which leads to a deeper understanding. Additionally, Teacher C employs a variety of teaching strategies to convey important concepts, which reinforces key ideas through multiple perspectives.

However, there are some areas where Teacher C's PCK could still be developed further. One area that requires attention is the effective use of analogies. Teacher C should ensure that analogies are clearly explained and their limitations explicitly stated to avoid misconceptions. Furthermore, he could boost his PCK by improving the connection between main ideas and intermediate concepts, which will help learners build a better understanding of abstract ideas, such as those in electric circuits.

Finally, there is evidence of how the representations employed by Teacher C affected the way learners interpreted, understood, and responded to items in the diagnostic test. The extent of this influence differed among learners; it sometimes enhanced their comprehension of both complete and incomplete circuits, as well as current flow in series and parallel circuits. However, it also occasionally led to misunderstandings or incorrect applications, such as misinterpreting the concept of short circuits. Regardless, there is a clear connection between the representations used and the learners' grasp of the concepts.

CHAPTER 5: INTERPRETATION AND FINDINGS

5.1 Introduction

The previous chapter presented the results of this study, while this chapter elaborates on the interpretation of the results and the findings of the study. This qualitative research study sought to explore the different representations teachers use in their CTS to improve learners' understanding of concepts related to electric circuits. Data for this study was drawn from three secondary schools, one in South Africa and two in Australia, using semi-structured interviews, document analysis, and a diagnostic test. This chapter begins with a summary of the various representations employed by teachers and explores the effect that these representations have on addressing major concepts and misconceptions in electric circuits. Additionally, the chapter addresses the limitations of some of the representations used by the teachers in this study, followed by an evaluation of the effectiveness of the teachers' PCK using them. Finally, the chapter concludes with an item analysis of the diagnostic test.

5.2 Summary of Representations Used by Teachers

Table 5.1 summarises and compares the various representations used by the three teachers in the current study as they taught the main topics of current, voltage, and resistance.

Teacher A used separate representations for each concept. She applied a colour-coding/ highlighting technique to represent and discuss current flow. For voltage, she used her people-charge analogy to explain how voltage is distributed throughout different parts of a series or parallel circuit. To describe how resistance changes when resistors are connected in parallel and its effect on overall current flow, she used a shop analogy.

Conversely, Teacher B adopted a simpler approach by using a single representation for all three concepts. She used a PhET simulation with worksheets that she created to investigate current, voltage, and resistance. These worksheets guided learners through the simulations, helping them explore the patterns and relationships in each concept.

Finally, Teacher C used two main representations. The first involved the use of circuit kits to examine the effects of series and parallel connections on current flow and, indirectly, on resistance. The second representation involved using a hosepipe analogy to describe the roles of current, voltage, and resistance in a circuit.

Table 5.1 – Summary of representations used by Teachers A, B and C

	Teacher A	Teacher B	Teacher C
Current	**Used colour pens to highlight** the paths that electrons take around a circuit while discussing the quantitative nature of current flow.	**PhET simulation with guided worksheet** to explore current relationships through series and parallel circuit connections.	**Circuit kits** to explore current relationships in series and parallel circuit connections. Used Christmas lights and lights in classroom as examples. Water flow in **hosepipe analogy**.
Voltage	**People-charge analogy** used to describe the quantitative nature of voltage through series and parallel connections.	**PhET simulation with guided worksheet** to describe the quantitative nature of voltage through series and parallel connections. Described voltage as a pushing force and referred to a domino effect.	Water pump in **hosepipe analogy** used only to describe concept.
Resistance	**Shop analogy** used for resistors connected in parallel.	**PhET simulation with guided worksheet** to explore resistance relationships through series and parallel circuit connections.	Constriction in **hosepipe analogy** used to describe concept. Resistance relationships addressed as part of current relationships.

5.3 Addressing Major Concepts and Misconceptions

5.3.1 The Start of the Teaching Programme in Electric Circuits

All three teachers began their teaching programme using a similar strategy, which involved assessing learners' prior knowledge and then introducing the simple concepts of electric circuits. Teacher A started with a class discussion to evaluate her learners' understanding from previous years, asking basic questions such as "What is a series circuit?" and "What is current and what is it measured in?". Teacher B also began with a discussion to gauge learners' background knowledge, but used the information gathered from this activity as a foundation to direct her teaching for the remaining teaching period. For example, she learned that her learners were not yet familiar with the symbol of a resistor and later showed how she incorporated this idea into her teaching. Teacher B also gave her learners an activity in which they had to draw circuit symbols and circuit diagrams and represent these on a PhET simulation before delving into the main content. Similarly, Teacher C's approach involved instructing learners to copy circuit symbols, participate in a matching activity, and draw circuit diagrams using those symbols, as evidenced by his slides.

All teachers revealed an important component of their PCK in their knowledge of learner understanding by providing opportunities for learners to expose their thinking (Chan et al., 2019). This finding is important because this is a similarity in their pedagogical approach to the beginning of the teaching programme despite the differences in their teaching approach later on in their respective teaching programmes. This is a reflection of that which can be found in the general knowledge bases of PCK according to the RCM (Carlson et al., 2019).

5.3.2 Distinguishing Between Voltage and Current

Responses from the learners to items in the diagnostic test revealed a common issue: learners had difficulty distinguishing between voltage and current. They frequently used the terms voltage and current interchangeably in their explanations, often relating energy to current. In most explanations, learners mentioned current frequently, while largely ignoring voltage. As documented by Burde and Wilhelm (2020), when learners think about circuit analysis, voltage is either seen as a part of, or subsequent to current, and current tends to be at the forefront of circuit analysis. In the current study, there is evidence to suggest that the teaching methods could have an impact on why current and voltage are misunderstood or used synonymously.

5.3.2.1 Current Behaviour in Series and Parallel Circuits

Teacher A explained how current behaves in series and parallel circuits by using her colour-coding technique' to highlight the paths that electrons take on a circuit diagram She used different colours to help learners visualise the concept. Teacher B employed inquiry-based learning by using the PhET simulation and a worksheet to guide learners to independently investigate the various current relationships in series and parallel circuits. Teacher C investigated the current flow in series and parallel circuits using circuit boards with ammeters. He provided two analogies: one using the functioning of a string of Christmas lights for series connections, and the other showing how the classroom lights still function even if one of the lights is not working for parallel connections.

The results from the diagnostic test indicate that regardless of the difference in teaching strategies used, the learners from all three teachers best understood the conditions needed for current to flow. Additionally, learners from all teachers had a good understanding of how current is distributed differently in series or parallel circuit parts. However, Teacher C's learners did not show as much success with current in parallel circuits and provided a variety of incomplete or incorrect responses, including one with reasons such as short circuits. This suggests that his use of circuit boards and/or his analogy did not prove to be as successful in getting learners to understand how current behaves in series and parallel circuits.

Table 5.3 (p. 119), Table 5.4 (p. 120), and Table 5.5 (p.121) summarise the major concepts and misconceptions of Teacher A, Teacher B, and Teacher C, respectively, the representations they used to teach these concepts, and how the learners performed in the diagnostic test items relating to these concepts. This approach highlights the link between the representation used by the teacher and how it is able to inform learner understanding.

5.3.2.2 Current as Amount of Charge per Second

Teacher A used a shop analogy to describe current as the rate at which people (charges) move through a queue. She provided the formula ($I = Q/\Delta t$) and defined it in words every time she addressed the concept in class. Teacher B did not use a specific formal representation for this idea, but instead explained to learners that current is “a measure of how much the electrons is moving in time”. With both of these techniques in mind, the learners of both Teacher A and Teacher B mention current as the flow or movement of charges but do not mention the flow <u>rate</u> or <u>amount of</u> charge. It is worth noting that current is not described as the rate of flow of charge in the CAPS document. Teacher C used a hosepipe analogy to represent current as the water flow rate through a hose. Despite this, none of his learners could explain current as the flow rate or movement of charge. Instead, they could only refer to current in its quantitative nature, i.e. the same in series circuits and split in parallel circuits.

5.3.2.3 Voltage as an Energy Concept

Teacher A and Teacher C both used an analogy to describe the role that voltage plays in different circuit connections. Teacher A’s people-charge analogy involved people collecting money (energy) from the cell and spending or using it (converting it) as they move through the resistors along their path (circuit). Teacher C used a hosepipe analogy to describe voltage as “the water pump that pushes the water through the hose”, but did not make an attempt to connect the analogy to the concept of energy. Both of these analogies have limitations, which are discussed later in this interpretation. Interestingly, across a range of items in the diagnostic test, learners from both Teacher A and Teacher C mentioned energy in their explanations. However, they used energy to describe both current and voltage behaviour interchangeably, showing that the analogy did not help them in distinguishing between the two concepts.

Teacher B explained voltage as "how much force is being used to push electrons to start to move" and acted out a pushing or domino effect. Similar to Teacher C, Teacher B's representation made no connection to energy. The results of the diagnostic test indicate that none of Teacher B's learners referred to energy in their explanations.

5.3.2.4 Voltage Behaviour in Series and Parallel Circuits

Teacher A used the same people-charge analogy as described above to explain the quantitative nature of voltage through series and parallel circuits. It is important to note that in the video resource, it can be seen that Teacher A used this analogy while colouring the path the electrons take as they move through the circuit. This means that voltage concepts are discussed together with current concepts, making it difficult for learners to understand why they are two distinct concepts. This is something that Burde and Wilhelm (2020) deem as a "major impediment for the development of conceptual understanding of voltage at a secondary school level" since the examples used in class typically discuss voltage and current together. Current is addressed first and in greater detail, whereas voltage tends to be perceived as a property of electric current. This also explains why Teacher A's learners used the terms current and voltage interchangeably in their explanations to items in the diagnostic test.

Teacher B continued using the PhET simulation and the worksheet she had prepared to guide her learners through her voltage rules of circuit analysis. The results of the diagnostic test show that Teacher B's learners had the most success in explaining voltage distribution in parallel branches, indicating that the PhET simulation had a positive effect in getting learners to understand this relationship.

Teacher C did not use any formal representation or explicitly teach about voltage, and instead focused almost exclusively on current and its behaviour in various circuit connections. As a result, his learners referred to current rather than voltage in their explanations during the diagnostic test, indicating they were less equipped to understand the difference between these two concepts and their interaction in a circuit.

In summary, although there is a connection between teaching strategies and the understanding or misunderstanding of concepts, what is also clear is that, regardless of the teaching method used, learners still struggled to differentiate between current and voltage.

5.3.3 Resistors Connected in Parallel

Item 5 in the diagnostic test addressed the idea that adding more resistors in parallel decreases the total resistance of the circuit and increases the current, contrary to the misconception described for parallel circuits. Results from learners across all three teachers revealed that this concept was challenging to grasp, leading to some interesting thought processes. These are discussed further below.

Teacher A addressed this idea with a shop analogy where the number of open counters in a shop (representing resistors connected in parallel) affects the rate at which people move through the queue (current). Teacher B did not address this concept and, during the interview, she revealed a misconception about local and sequential reasoning herself. Although Teacher C did not formally address this concept, he did encourage his learners to apply their previous knowledge to think about the relationship between resistors in parallel and total resistance. The responses to this item were so intriguing that the decision was made to compile the findings into Table 5.2, with specific emphasis on Option D.

Table 5.2 – Summary of answer selection in Item 5 of the diagnostic test

Option Selection:		**A. Correct Answer**	**C. Parallel Circuit Misconception**	**D. No Effect on Brightness of Bulb**	
Notes regarding the addressing of this idea		**(%)**	**(%)**	**(%)**	**Most prevalent explanation provided**
Teacher A	Analogy for this idea. Question in the worksheet.	24	40	36	"The current is travelling anticlockwise, so it moves through the light bulb first in all circuit".
Teacher B	Not addressed. Teacher B reveals "no effect on brightness of bulb" herself.	38	24	38	"The resistor only comes after the light bulbs in all three diagrams therefore the resistors don't affect them".
Teacher C	Not addressed. Learners needed to apply knowledge to answer it themselves.	7	21	72	"Because it takes the easiest route, and for that to be accomplished it has to go through one, and only one".
Total percentage of the 47 learners who took the test across the three teachers		10	32	47	

Two significant discoveries emerged after analysing the responses to this item. Firstly, contrary to expectations, the majority of learners chose Option D over Option C, which would have revealed the common misconception regarding parallel circuits. Secondly, the rationale behind choosing Option D proved to be even more interesting. It became evident that the teachers' instructional approaches, or lack thereof, played a crucial role in influencing learner responses.

Teacher A's shop analogy, while intended to clarify the concept, had limitations that potentially led to confusion or alternative interpretations. For example, since people in a shop move through one counter regardless of which one they pick and hence all take the same route, so electrons move through one resistor regardless of how many resistors are available, which has no effect on the current flow throughout the circuit. The results also show that this item was the most poorly answered item out of all the items in the test for her learners.

Teacher B, who had a misconception herself (believing that adding more resistors in parallel would not affect the current in the external circuit), may have unknowingly influenced a significant portion of her learners to reason incorrectly about adding resistors in parallel. Many learners assumed that the change in the circuit occurs after the light bulb (using sequential reasoning) and therefore has no impact on its brightness.

Conversely, Teacher C's hands-off approach allowed learners to rely on and apply their existing knowledge to a new idea. This approach increased the risk of using of incorrect or alternative ways of thinking. For example, since he had concluded the topic by teaching short circuits, many learners actually used this idea as a reason for their answer selection in Item 5.

This finding once again reveals that there is indeed a connection between the representation that the teacher uses and how learners reason and understand concepts in electric circuits. This is an important contribution to answering research Question 3 of this study.

The local and sequential reasoning misconception, where learners think that changes in circuits have only a local effect rather than an effect on the whole circuit (Sencar & Eryilmaz, 2004), was prevalent in the selection of Option D for all learners across the three teachers. However, learners provided a variety of reasons based on the representation (or lack thereof) used by their teacher.

The learners reasoned that no matter how many resistors are added in parallel, the brightness of the light bulbs remains the same because whatever is in the path that the electrons take is the same. In all three circuits, each charge only moves through one resistor and one light bulb

(Figure 5-1). This means that learners did not acknowledge that the addition of more resistors in parallel decreases the total resistance of the entire (external) circuit, which in turn affects the current of the entire (external) circuit. Teacher C's learners referred to this path as the path of least resistance because the charges will only choose one resistor (and not three) to move through. Teacher A's learners' reasoned that the current moves anticlockwise (which happens to be the same direction in which she moved her coloured pen in the video resource that she provided) and, since the change happens AFTER the light bulb, it does not affect the brightness of the light bulb. Teacher B's learners' reasoned the same way.

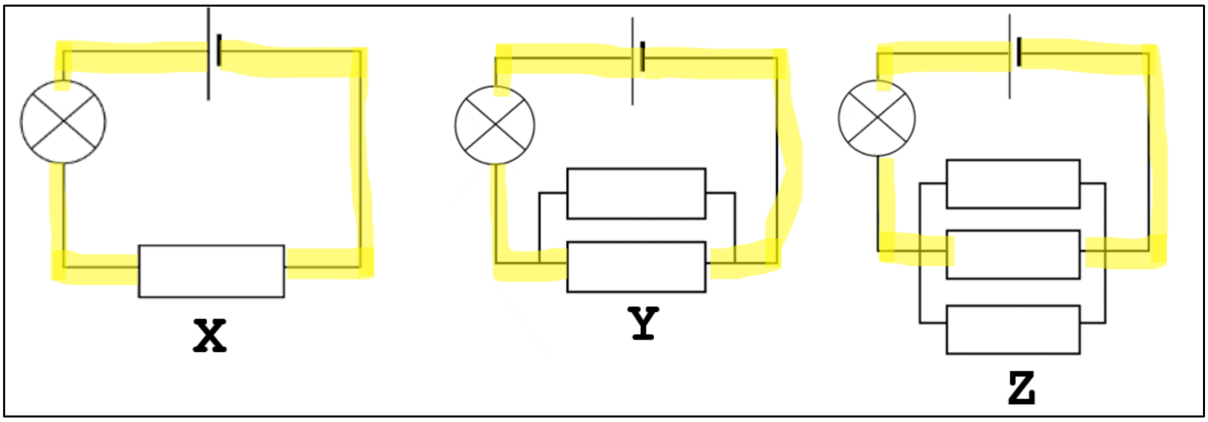


Figure 5-1 – Different paths that electrons could follow around the circuit in Item 5

Table 5.3, Table 5.4, and Table 5.5 summarise the findings in the discussion above to display the link between the representation used by each teacher to address major concepts and misconceptions in electric circuits and learner performance to items in the diagnostic test that address these concepts.

Items Included: Seven main ideas common to all three teachers were included in the summary table for clarity. Items 2, 4, 5, and 7 were selected as they provided significant insights from both the teachers' lesson plans and the learners' diagnostic test responses.

Items Not Included: Items 1, 10, and 11 were excluded as they presented broad concepts not fitting within the series or parallel circuit categories. Item 8 was excluded due to its focus on cell connections arranged in both series and parallel, making it incompatible with either category. Item 3 was excluded because its concepts were repeated in Item 2, and Item 9 was excluded due to its focus on short circuits. Finally, Item 6 was excluded as the learner responses lacked sufficient detail to draw conclusions

Table 5.3 – Summary of how Teacher A addressed major concepts and misconceptions and her learners' responses to diagnostic test questions relating to these concepts

Major concepts and typical misconceptions	**How these concepts were addressed (representations)**	**Learner responses to questions in diagnostic test that addressed these concepts**	
		% Correct	**Additional notes**
Current in series circuits	Used colour pens to highlight the parts of a circuit where there is one pathway for the electrons to travel through. The same colour or combinations of colours were used for these parts.	**Item 2: Current flow in series circuits**	
		88	Explanations included phrases with terms such as "broken, incomplete circuit, no pathway, open circuit".
Current in parallel circuits	Highlighted the different pathways through which electrons travelled on a circuit diagram using different colours.	**Item 4: Current flow through branches in a parallel circuit**	
		72	Explanations included phrases with terms such as "split, divide, same current flowing through series, more options or pathways".
Current as amount of charge per second	Shop analogy described current as the rate at which people (charges) move through the queue (current). Formula ($I = \frac{Q}{\Delta t}$) with definition written on board when topic was addressed in class.	Explanations provided across test items display current as a flow of charges, however, no reference is made to the <u>rate at which</u> these charges flow or to a change in the <u>amount of charge</u>.	
Voltage as an energy concept	People-charge analogy described the cell as a source of energy where energy is to be used up throughout the circuit. Formula ($V = \frac{W}{Q}$) with definition written on board when topic was addressed in class. Redox reactions and standard reduction potentials table were used to introduce the energy difference idea.	Explanations provided across test items reveal that learners make no distinction between current and voltage and view them both as an energy concept, i.e. learners explain changes in current or voltage in test items by referring to changes in energy.	
Voltage behaviour in series circuits	People-charge analogy: People collect money (energy) from the cell and spend it (convert it) as they move through the resistors along their path.	Explanations across questions included phrases like "voltages of components add up to that of the battery/cell".	
Voltage behaviour in parallel circuits		**Item 7: Voltage through parallel branches**	
		56	Most explanations reveal an understanding that voltage across parallel branches is the same as of the total voltage across the cell. The remaining displays how voltage adds up to the total voltage, dividing according to the resistance of each parallel branch.
The more resistors connected in parallel, the lower the total resistance	Shop analogy: The number of open counters in a shop (resistors connected in parallel) affect the rate at which people move through the queue (current).	**Item 5: More resistors in parallel, lower total resistance; higher total current**	
		24	Learners understand the analogy but cannot apply it effectively. Teacher did not provide an example similar to this question in a worksheet issued to her learners.

Table 5.4 – Summary of how Teacher B addressed major concepts and misconceptions and her learners' responses to diagnostic test questions relating to these concepts

Major concepts and typical misconceptions	**How these concepts were addressed (representations)**	**Learner responses to questions in diagnostic test that addressed these concepts**	
		% Correct	**Additional notes**
Current in series circuits	PhET simulation alongside Worksheet A where learners investigate different relationships independently.	**Item 2:** **Current flow in series circuits**	
		88	All correct explanations mentioned a break in circuit or an incomplete circuit.
Current in parallel circuits	PhET simulation alongside Worksheet A where learners investigate different relationships independently.	**Item 4:** **Current flow through branches in a parallel circuit**	
		88	Most explanations only referred to the branch with P and Q – saying that current is the same. No reference was made to the rest of the circuit.
Current as amount of charge per second	No formal representation. Explained to learners in class as "a measure of how much the electrons is moving in time". Learners briefly asked in worksheet to provide a definition for current.	Explanations across questions make mention that current has flow or that there is movement of charges; however, no reference is made to the rate at which these charges flow or to a change in the amount of charge.	
Voltage as an energy concept	No formal representation and no connection made to ENERGY. Explained to learners in class as "how much force is being used to push electrons to start to move". Used acting to simulate a pushing or domino effect.	No mention of energy in any of the learners' explanations to any questions in the diagnostic test.	
Voltage behaviour in series circuits	PhET simulation alongside Worksheet A where learners investigate different relationships independently.	In a few explanations across questions, mention is made of voltages in a series circuit adding up to that of the cell or being distributed proportionally.	
Voltage behaviour in parallel circuits		**Item 7:** **Voltage through parallel branches**	
		88	Evidence of quantitative understanding only: that voltage across resistors in parallel (only) is the same as the total voltage (cell).
The more resistors connected in parallel, the lower the total resistance	Not addressed. Misconception revealed in Teacher B.	**Item 5:** **More resistors in parallel, lower total resistance; higher total current**	
		38	No accurate explanation provided. Learners revealed to be in possession of the local and sequential reasoning misconception as well as the parallel circuit misconception.

Table 5.5 – Summary of how Teacher C addressed major concepts and misconceptions and his learners' responses to diagnostic test questions relating to these concepts

Major concepts and typical misconceptions	**How these concepts were addressed (representations)**	**Learner responses to questions in diagnostic test that addressed these concepts**	
		% Correct	**Additional notes**
Current in series circuits	Circuit boards with ammeters used to investigate current flow in series circuits. Christmas light analogy. Practice worksheet provided.	**Item 2: Current flow in series circuits**	
		93	Explanations included phrases with terms such as "break, hole or incomplete circuit".
Current in parallel circuits	Circuit boards with ammeters used to investigate quantitative nature of current in parallel circuits. Classroom lights example. Practice worksheet provided.	**Item 4: Current flow through branches in a parallel circuit**	
		36	Variety of mixed responses. Only a few correct explanations use phrases such as "on the same line" or "on the same section". Some incorrectly mention an equal split between branches regardless of resistance. One mentions the path of least resistance.
Current as amount of charge per second	Hosepipe analogy to represent current as water flow rate through a hose.	Explanations to questions make no mention of current as a flow rate. Only mention made is to quantitative nature of current in different connection types.	
Voltage as an energy concept	No formal representation and no connection made to ENERGY. Hosepipe analogy used to represent voltage as "the water pump that pushes the water through the hose".	Explanations make reference to energy; however, this is used interchangeably when reference is made to either voltage or current.	
Voltage behaviour in series circuits	No formal representation used in class or mentioned in interview. One question present in worksheet.	No mention of the quantitative nature of voltage. Energy distribution between components in a circuit is mentioned, but no connection of this is made to voltage.	
Voltage behaviour in parallel circuits	No formal representation used in class or mentioned in interview. One question present in worksheet.	**Item 7: Voltage through parallel branches**	
		50	Explanations provided for the correct option selection were either incorrect, incomplete or deliberately avoided.
The more resistors connected in parallel, the lower the total resistance	No formal representation used. Teacher encouraged learners to apply previous knowledge to think about this relationship.	**Item 5: More resistors in parallel, lower total resistance; higher total current**	
		7	One learner selected the correct option with the explanation lacking detail. The remaining 83% of responses reflected possession of local and sequential reasoning and parallel circuit misconception.

5.4 Addressing Limitations of Representations

Evidence in literature suggests that various representations are used to teach topics in science, such as electric circuits, and that these representations make a contribution to how learners understand different ideas (Balta, 2015; Kapici et al., 2019; Reisslein et al., 2014). Representations are valuable tools in science education to promote understanding as long as their strengths and limitations are considered carefully and stated explicitly (Guerra-Ramos, 2011; Oliveira & Bonito, 2023). The current study exposed the negative effects on some learners of not making the limitations of a representation clear while using it, which was to the learners' detriment. A discussion of how this manifested in each of the three teachers follows.

5.4.1 Teacher A

Teacher A used colour coding to explain the flow of electrons. However, in the video, she unconsciously moved her highlighter in the direction of conventional current (Figure 5-2). There is a possibility that this could later confuse her learners about which type of charge is really moving (positive or negative). More importantly, the negative effect of the use of this representation is reflected in the learners' responses to Item 5 in the diagnostic test: many reasoned that the current is moving anticlockwise – the same direction that Teacher C would have used when colour coding – and, therefore, the charge goes through the light bulb first before the resistors. The learners reasoned that changing the resistors would not affect the brightness of the bulb. Similarly, it is possible that despite Teacher C using this representation to demonstrate the movement of electrons in the opposite direction (through the resistors first), learners may still reason that electrons travel through only one resistor and, therefore, the change would not affect the brightness of the bulb. Both these scenarios display the sequential reasoning misconception (Sencar & Eryilmaz, 2004).

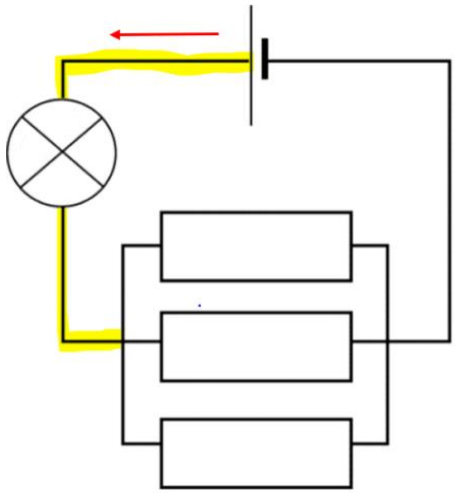


Figure 5-2 – Direction of current as viewed by learners in the diagnostic test

Teacher A's use of analogies had limitations as well. Her first analogy compared charges to people who spend money (or use energy) to go through components before returning to the cell to collect more energy. However, this analogy could lead learners to think of the cell as a constant current source (Sencar & Eryilmaz, 2004) and overlook the idea that energy is converted at different components rather than being used up. When introducing the analogy, she should clearly explain these two important specifications to her learners to avoid incorrect thinking in their future science careers. Her second analogy, for resistors connected in parallel, required her to explicitly state that opening up more counters in the shop (resistors in parallel) would not lead to more people in the queue (more charges) but rather increase the rate at which these people move through the queue (rate of flow of charge). This specification may make it easier for her learners to understand the current as a <u>rate of flow of charge</u> (since they did not refer to the rate of charge flow in the diagnostic test) and decrease the likelihood of viewing current as the speed at which charges move through the circuit.

Finally, it is observed that even small errors made unconsciously by teachers can affect how learners reason scientifically. As discussed earlier in the analysis, Teacher A's wording contradicts what is diagrammatically displayed in one PowerPoint slide (Figure 5-3). The learners' responses to items in the diagnostic test that addressed voltage in parallel connections indicated the consequences of such an error as they repeated this "adding up" phenomenon. Teachers need to be careful when choosing their words to describe phenomena in science topics to ensure that what is meant to be communicated is done so in the most accurate way possible to avoid alternative ways of thinking.

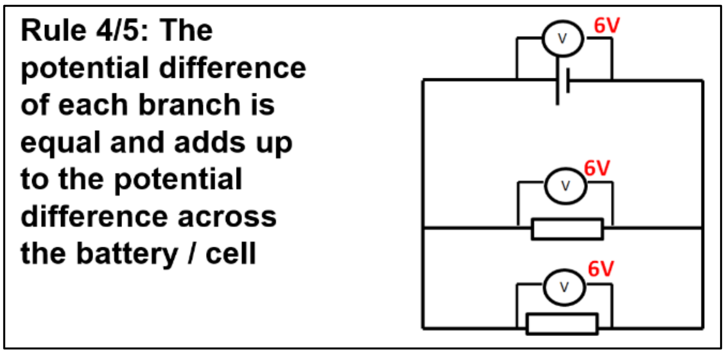


Figure 5-3 – Incorrect information in one of Teacher A's PowerPoint presentation slides

5.4.2 Teacher B

Just as Teacher A's choice of words led to learners misunderstanding scientific relationships, Teacher B's minor errors in her worksheets may have incorrectly shaped her learners' thinking and reasoning. As mentioned in the analysis, using phrases such as "side by side" for resistors connected in parallel may create a false image about what series and parallel really means. I do, however, believe that Teacher B actually made a stronger attempt at getting her learners to understand the difference between current and voltage than the other two teachers. It seemed that she gave her learners an opportunity to explore each concept first, before putting the two ideas together and discussing how their values differ from each other. By using inquiry-based worksheets and the PhET simulation, learners were given opportunities to examine concepts separately before exploring how they function together.

While this type of learning has its benefits, the risks that come with independent learning, especially those associated with simulations (Almasri, 2022), should always be considered. Independent learning has the potential to create misconceptions that are difficult to correct since learners are solely responsible for intuitively figuring out why things happen the way they do (Nkopane et al., 2011a). This may explain why her learners struggled to provide accurate explanations of the difference between current and voltage.

Teacher B also used an acting demonstration and a domino effect analogy to explain voltage, showing how the cell exerts a pushing force to move electrons around the circuit. However, this analogy is not consistent with the way that voltage really works. As a result, it is recommended that it not be used to describe voltage as a concept or the role it plays in different circuit connections. For learners familiar with dominoes, it may incorrectly suggest that when a cell is initially connected to a circuit, it pushes the nearest electron forward, which in turn does the same to the following electron. In so doing, each electron's movement depends on the force applied by the preceding electron. The disadvantages of this representation outweigh its advantages, making it unsuitable for teaching electric circuits. While none of Teacher B's learners explicitly used the term "domino" in their responses, Item 9 of the diagnostic test (as discussed in Chapter 4) revealed reasoning that aligns with the domino effect concept. This perspective helps to understand why the learners arrived at their conclusions.

5.4.3 Teacher C

Similarly, Teacher C's water pump analogy has value in helping learners visualise the effect of resistance on current flow. However, the limitations of always relating voltage to water pressure or current to water flow should be clearly stated in case learners apply this analogy to all examples in electric circuits. This could lead to multiple misconceptions (Brown & Salter, 2010).

5.4 Teachers' PCK Regarding the Effective Use of Representations

Studies have shown that the PCK components of knowledge of learner understanding of science and of CTS and representations are most significant in successful learning (Berry et al., 2015; Nilsson, 2014; Park & Chen, 2012). In a study to explore the enacted PCK of teachers across concepts in electrostatics, Mazibe et al. (2023) used three PCK components to assess and quantify teachers' PCK. Two out of the three aforementioned components remained the same: (1) learner understanding of science and (2) CTS, including representations. We focus on the latter for the purpose of this interpretation.

In this study, there were instances where the teachers' PCK regarding CTS, specifically representations, was deemed limited or in need of development, especially in relation to the use of analogies. Both Teacher A and Teacher C used analogies in their teaching, but with significant limitations. During the interview, both Teacher A and Teacher C discussed how the analogy relates to concepts in electric circuits. However, they did not provide specific details on how this analogy was presented to the learners. In an article by Brown and Salter (2010), it is emphasised that understanding the components of an analogy is crucial for discerning its intended meaning. Their article discusses strategies that can help with correctly interpreting analogies (Brown & Salter, 2010):

1. Educate learners about the nature of <u>analogies</u>.
2. Craft <u>analogies</u> carefully to ensure clarity and relevance.
3. Clearly outline the structure of <u>analogies</u> and acknowledge their limitations.
4. Use multiple <u>analogies</u> when necessary.

When using analogies as representations, it is important to carefully consider how the analogy will be presented to learners. It is crucial to highlight and discuss the analogy's strengths and weaknesses before or during its use. This was something that was not considered for any of the analogies used by teachers in the current study.

It is suggested that the argument for discussing the salient points of an analogy also applies to <u>any representation</u>. For example, when using a scientific diagram to explain a concept, teachers should discuss both its strengths, such as accurately showing certain aspects, and its limitations, including what it may be unable to depict or how it could be misinterpreted.

Therefore, the same strategies used by Brown and Salter (2010) to present analogies can be used in the presentation of representations:

1. Educate learners about the nature of <u>representations</u>.
2. Craft <u>representations</u> carefully to ensure clarity and relevance.
3. Clearly outline the structure of <u>representations</u> and acknowledge their limitations.
4. Use multiple <u>representations</u> when necessary.

5.5 Analysis of Responses to Items in the Diagnostic Test

What follows is a brief discussion of how learners from all teachers performed in each item of the diagnostic test, an interpretation of this finding, and an analysis of the effectiveness of the item. Following the discussion, Table 5.6 summarises the learners' responses across all teachers for each item in the diagnostic test.

5.5.1 Item 1: Origin of Charges

Item 1, sourced directly from the DIRECT test (Engelhardt & Beichner, 2004), prompted learners to consider the origins of electrical charges before they move through a circuit. Since the item did not require learners to explain their selection, it was not as effective in linking the representation used by the teacher to the learners' understanding of the concept, as compared to other items. The PowerPoint presentations from Teacher A and Teacher C provide evidence that they addressed the concept of cells as sources of energy, whereas Teacher B did not include such information. Interestingly, Teacher C's learners performed the best on this item, whereas Teacher A's learners performed the worst, although their average score of 60% is still commendable. The South African curriculum explicitly requires addressing cells as an energy source (Department of Basic Education, 2011a), while the Australian curriculum is less prescriptive regarding teaching this topic (NSW Education, 2018). The item is significant since understanding the origin and movement of electrons is fundamental in studying electricity. Research indicates that many learners hold the misconception that electrons come from the battery (Gucluer, 2020; Yang et al., 2004). Therefore, it is beneficial for learners to have opportunities to explore and challenge their misconceptions.

5.5.2 Item 2: Closed Circuit Conditions

Item 2 was designed by the researcher for the purpose of the current study. For all three teachers, this was the best-answered question in the diagnostic test, indicating that most learners understood the difference between closed and open circuits and the consequences of a malfunctioning circuit component. There was no evidence in Teacher A's PowerPoint presentation or interview that she explicitly taught or addressed this concept. Teacher B's use of the PhET simulation throughout her teaching programme meant that the learners had to create closed circuits as part of all their investigations, thereby reinforcing their understanding. Teacher C taught this concept directly, using a similar approach as the one in the diagnostic test. It was incorporated into his PowerPoint presentation and worksheets. Consequently, Teacher C's learners outperformed the other learners on this particular question.

5.5.3 Item 3: Brightness of Bulbs In Series

Item 3 was designed by the researcher for the purpose of the current study. Its inclusion provided significant insights into how learners reason about current flow based on their explanations. Learners from Teacher A and Teacher B's classes were less successful than those from Teacher C's class in answering this question, with many demonstrating the empirical rule and current weakening misconception. It is possible that Teacher A's use of a colour-highlighted path for electrons may have caused learners to incorrectly conclude that the current is used up by one light bulb before reaching another. This is because her colour would reach one light bulb before the other. In the case of Teacher B, this poor result is unexpected since the PhET simulation demonstrates that light bulbs light up simultaneously and that they shine with the same brightness. This suggests that the simulation might not have effectively conveyed the intended concept and that Teacher B could have been more specific with the questions on her worksheet. By doing so, learners' attention could have been better focused on features like the one mentioned, which can easily be overlooked. Conversely, Teacher C's learners outperformed all the learners who took the test. This is likely because he directly and explicitly addressed the concept in his PowerPoint presentation and facilitated classroom discussions about the brightness and lighting of light bulbs. During his interview, Teacher C mentioned that he believes his learners' success on this question is connected to him addressing the concept during class.

5.5.4 Item 4: Current in Series and Parallel Connections

Item 4 was related to Item 17 in the DIRECT test (Engelhardt & Beichner, 2004), but it was rewritten by the researcher for the purpose of the current study. Although the item is valuable, its complexity may have distracted learners. The circuit provided was a parallel one, which required knowledge of current splitting. However, the correct answer related to series circuits, a topic that had already been covered in previous questions. Therefore, this question needs revision and simplification. Despite this, learners from Teacher B's class performed the best, mostly using their knowledge of series circuits. Teacher A's learners also performed well, incorporating elements of her representations in their explanations. On the other hand, Teacher C's learners struggled with this question despite building physical circuits similar to the one shown in the item. Their explanations to their item selection were incomplete and lacked depth.

5.5.5 Item 5: Resistors Connected in Parallel

Item 5 was related to Item 29 in the DIRECT test (Engelhardt & Beichner, 2004), but it was rewritten by the researcher for the purpose of the current study. This item proved to be valuable as it highlighted a range of alternative ways of thinking among learners. It was one of the more challenging items in the diagnostic test, reflected in the poor performance by all learners across the three teachers. Teacher A was the only teacher to explicitly address the concept, though her flawed analogy may have inadvertently created misconceptions rather than enrich understanding. Teacher C did not teach the concept at all, and since most of his learners got this question incorrect, they were not able to intuitively discover the relationship on their own – something that he hoped would happen as mentioned in the interview. Notably, Teacher B's learners achieved the highest percentage of correct answers, although it was still low. This suggests that inquiry-based learning might be more effective in fostering correct thinking about difficult concepts than analogies.

5.5.6 Item 6: Voltage of Resistors in Parallel

Item 6, sourced directly from the DIRECT test (Engelhardt & Beichner, 2004), addressed voltage in parallel circuits. However, this concept was already covered by two other test items, thus it would be more appropriate to replace it with an item focusing on the quantitative relationship of voltage in series – an essential outcome expected to be taught by all three teachers. Therefore, the item requires revision despite being relatively well-answered (with average scores above 60%) by learners across all teachers. The item provided valuable insights into learners' thinking about voltage by revealing persistent confusion between the concepts of current and voltage. Learners frequently interchanged these terms in their explanations of potential difference.

5.5.7 Item 7: Current and Voltage in a Parallel Circuit

Item 7 was designed by the researcher for the purpose of the current study. Similar to Item 4, it is perceived that this item asked learners to address too many concepts simultaneously. The item required learners to select the option that accurately represented both current and voltage in a circuit. For Grade 9 learners who are just beginning to understand basic circuit analysis and how current and voltage are distributed in different connections, addressing two different concepts at once could prove overwhelming and could make the item redundant. This is evident in their responses as many struggled to explain their selection fully. Teacher C's learners, for example, either provided partial explanations or failed to address both current and voltage. Interestingly, regardless of the representation used or the teacher's approach, learners from all classes primarily considered current before examining voltage. Notably, Teacher B's learners performed significantly better than the others, demonstrating the positive effects of inquiry-based learning.

5.5.8 Item 8: Cells Connected in Series Compared to Parallel

Item 8 was based on Item 3 in the DIRECT test (Engelhardt & Beichner, 2004), but was altered by the researcher. While the concept of cells connected in parallel is included in the South African curriculum (Department of Basic Education, 2011a), it is not explicitly stated in the Australian curriculum (NSW Education, 2018). As a result, only Teacher A addressed this concept by referencing a question from the learner textbook and using her shop analogy to explain parallel connections. However, she admitted during the interview that her learners still did not fully understand it. Teacher B and Teacher C did not directly cover the concept in their teaching, and the learners' reasoning revealed little understanding of how different cell connections alter the circuit's total energy supply. Interestingly, despite being the only teacher to have addressed the concept with her learners, Teacher A's learners performed worse than those of Teacher B and Teacher C.

5.5.9 Item 9: Short Circuits in Parallel Connections

Item 9, which was altered but based on Item 19 in the DIRECT test (Engelhardt & Beichner, 2004), was effective for assessing understanding of short circuits as it required learners to challenge their thinking on the topic. The overall performance was low for learners across all teachers, which was expected for Teacher A and Teacher B since they did not directly address the concept. However, it was notable that despite Teacher C explicitly teaching short circuits, as confirmed in his interview and shown in his PowerPoint presentation, only 28% of his learners answered correctly. Moreover, they used short circuits as reasoning for items in other questions: some completely unrelated to short circuits. This suggests that Teacher C should perhaps approach this concept in a way similar to how he taught the concept of current (circuit kits) since his learners showed more success with those items.

5.5.10 Item 10: What Happens When Cells Become Flat

Item 10 was designed by the researcher for the purpose of the current study. The value that Item 10 holds is displayed in the connection that it has to similar concepts in Item 1. Specifically, Item 1 focuses on the origin of electrons, while Item 10 addresses the implications of batteries becoming flat, indirectly revisiting the misconception that charges, originating from within a cell, can be depleted. This indicates that if learners harbour the misconception about the origin of charges in Item 1, it might resurface in Item 10. Notably, Teacher A and Teacher B's learners performed similarly on both items, confirming this linkage. However, Teacher C's learners excelled in Item 1 but performed poorly on Item 10, indicating an incomplete understanding of the origin of charges and the role of the battery.

5.5.11 Item 11: Voltmeter Connected in Series

Item 11 was designed by the researcher for the purpose of the current study. In the South African curriculum, connecting voltmeters in parallel across components is part of the suggested practical activities. However, the understanding of why this needs to be so is not as explicit (Department of Basic Education, 2011). This concept is, however, not clearly stated as a requirement in the Australian curriculum (NSW Education, 2018). Based on learner responses to this item, it was evident that their understanding was directly linked to whether or not the teacher had taught the concept; therefore, no specific representation used by the teachers could be connected to this item. Teacher B and Teacher C did not address why a voltmeter needs to be connected in parallel – a possible shortcoming of their teaching and something which was reflected in their learners' performance: none of Teacher B's learners and only two of Teacher C's learners answered correctly. During the interview, Teacher A confirmed that she briefly addressed this concept with her learners, and as evidenced by their performance, her learners outperformed all others on this item. Interestingly, whether the concept was taught to learners or not, a common response from learners across all teachers was that voltmeters just "measure" and therefore have no resistance. This misconception presents a useful teaching point that teachers can use when discussing how different apparatus work in circuits or what their specific roles are.

Table 5.6 on the next page summarises the learners' responses across all teachers for each item in the diagnostic test.

5.6 Conclusion

This chapter interpreted the findings of the study based in data collected through the interviews, lesson plans (document analysis), and the analysis of the diagnostic test. The following chapter concludes the study by answering the research questions, discussing the implications and limitations of this study, and making recommendations for future study.

Table 5.6 – Summary of learner responses to each item in the diagnostic test

Major concepts	**Main representation**	**Teacher A**		**Teacher B**		**Teacher C**	
		Colour-coding technique, and people-charge and shop analogies		**PhET simulation and worksheet**		**Circuit kits, hosepipe analogy, and Christmas lights and classroom light examples**	
	Item no.	**% Correct**	**Additional notes**	**% Correct**	**Additional notes**	**% Correct**	**Additional notes**
Charges in wires	**1**	60	General understanding. Teacher A did address this concept at the start of her teaching programme.	63	General understanding. No evidence provided that this idea was covered.	72	General understanding. Teacher C addressed where electricity comes from at the start of his teaching programme.
Closed circuit conditions	**2**	88	Best answered out of the 11 items.	88	Best answered out of the 11 items.	93	Best answered out of the 11 items. Concept directly addressed by teacher.
Brightness of bulbs in series	**3**	68	Learners who selected the incorrect option revealed possession of empirical rule and current weakening misconception.	38	Learners who selected the incorrect option revealed possession of empirical rule and current weakening misconception.	93	Best answered out of the 11 items. Concept directly addressed by teacher.
Current in series and parallel	**4**	72	Explanations reflected use of teacher representation.	88	Best answered out of the 11 items. Explanations referred to series part. No elaboration for parallel part.	36	Variety of mixed responses for correct and incorrect option selection.

Table 5.7 (continued).

Resistors connected in parallel	**5**	24	Worst answered out of the 11 items. Addressed through shop analogy.	38	Not directly addressed by teacher.	7	Worst answered out of the 11 items. Not directly addressed by teacher.
Voltage of resistors in parallel	**6**	68	Addressed through people-charge analogy.	63	PhET simulation with worksheet.	64	Not directly addressed by teacher.
Current and voltage in parallel circuit	**7**	56	Some evidence in explanations of representation used incorrectly.	88	Best answered out of the 11 items. Evidence of quantitative understanding.	49	Explanations either incorrect, incomplete or avoided.
Cells in parallel	**8**	48	Concept addressed by teacher.	50	Concept not directly addressed by teacher.	57	Concept not directly addressed by teacher.
Short circuit in parallel connection	**9**	35	Not directly addressed by teacher.	25	Worst answered out of the 11 items. Not directly addressed by teacher.	28	Concept discussed thoroughly in class.
Charges when cells become flat	**10**	60	No evidence of directly addressing this except for teaching concept in Item 1.	63	No evidence of Teacher B directly addressing this.	28	No evidence of directly addressing this except for teaching concept in Item 1.
Voltmeter connected in series	**11**	56	Concept addressed by teacher.	0	Worst answered. Concept not addressed by teacher.	14	Concept not addressed by teacher.

CHAPTER 6: CONCLUSION

6.1 Introduction

In this chapter, the final discussion of the study's findings from previous chapters is presented. This discussion provides an overview of the study, addresses the research questions that guided the study, and draws conclusions based on the collected and analysed data. Additionally, the chapter discusses the limitations of the study and offers recommendations for future research and practice.

6.2 Overview of the Study

This study sought to investigate the link between the way in which teachers use representations to teach electric circuits and how this informs learners' conceptual understanding of this topic. The topic of electric circuits was chosen because it has been widely recognised in both international literature (Aligo et al., 2021; Cohen et al., 1983; Engelhardt & Beichner, 2004) and South African literature (Nkopane et al., 2011b; Ogegbo et al., 2019; Ramnarain & Moosa, 2017) as a topic that learners find difficult to understand. A review of existing literature revealed that misconceptions about electric circuits arise frequently and learners still have a limited conceptual understanding of related concepts (Aligo et al., 2021; Helm, 1978; Sencar & Eryilmaz, 2004).

DIRECT was designed specifically to help identify misconceptions and evaluate conceptual understanding of these ideas (Engelhardt & Beichner, 2004). Due to the complexity of the topic, extensive research has been conducted to explore various teaching strategies for the effective teaching and learning of electric circuits (Brown & Salter, 2010; Gottschlich et al., 2024; Ronen & Eliahu, 2000). The topic of electric circuits is an important part of both senior education and further education and training phases in the South African curriculum (Department of Basic Education, 2011a) as well as the Australian curriculum for learners in Grade 8 to Grade 11 (NSW, 2024). As long as this topic continues to be viewed as a complex part of the science curriculum, there will always be a need for ongoing investigation to determine the most effective teaching approaches. In the context of this study, effective teaching of electric circuits refers to teaching practices that result in learners developing an accurate conceptual understanding.

Accordingly, this study explored teaching of electric circuits by investigating the specific use of representations within teaching approaches and how the use influences learners' conceptual understanding. Science teachers who teach the topic of electricity and electric circuits to learners in Grade 9 were selected as participants for the study. The participants in this study were selected based on the location of the researcher at the time of data collection. Three teachers (one from South Africa and two from Australia) and their Grade 9 learners were conveniently included as part of the study population. In Grade 9, learners are introduced to important ideas such as current, voltage, and resistance, and how they manifest in both series and parallel connections.

The following methodology was used for this study: Participating teachers taught the required content related to the topic of electric circuits according to their planning to the participating learners. At the end of the teaching period, a diagnostic test, designed by the researcher, was completed by the learners, which was later analysed. Thereafter, each participating teacher was subjected to a semi-structured interview with the researcher. The qualitative data was collected through interviews with the three teachers, the resources they used to teach the topic at the time of the research, and the responses and explanations provided by learners in the diagnostic test. To ensure validity, all learners completed the diagnostic test during the final lesson on electric circuits when the content was still fresh in their minds and could be applied effectively. Additionally, learners were requested to complete the tool on their own without any additional assistance from their teacher or peers.

This methodology, which is based on the interpretivist paradigm, followed a qualitative approach since the data collected was non-numerical in nature. This approach provided deeper insights into the participants' experiences (Tenny, 2022). Additionally, a qualitative research approach was better suited for reflecting on the teachers' understanding and application of their PCK when teaching electric circuits.

The methodology was guided by the conceptual and theoretical framework, which was also used to analyse the data in order to answer the research questions. For this study, the theoretical framework was based on the RCM that conceptualises the idea of the PCK of teachers (Carlson et al., 2019). The study focused on the personal PCK of teachers, which includes both their unique knowledge gained from current and prior teaching experiences and, by extension, their enacted PCK, which refers to a subset of personal PCK and knowledge instinctively displayed through planning, teaching and then reflecting in the classroom.

In order to gain insight into their personal and enacted PCK, the two specific PCK components suggested in the grand rubric (Chan et al., 2019) were used to analyse the data collected. These two components include (1) knowledge and skills related to CTS, and (2) knowledge and skills related to the learners' understanding of science. Data collected for the *first* *component* was gathered through the semi-structured interviews of the participating teachers and any additional resources or planning provided to address how teachers apply their PCK when teaching electric circuits to Grade 9 learners. This essentially addressed secondary Research Question 1:

> *How do the teachers enact their PCK, as revealed in their lesson planning and reflections during interviews regarding the use of their own representations to teach concepts in electric circuits to Grade 9 learners?*

Data for the *second component* of the conceptual framework (learner understanding of science) was collected, first through the use of the diagnostic test that the learners completed and submitted and, second, through teacher interpretations of their learners' understanding in the interview to evaluate learner comprehension. This information aided in answering secondary Research Question 2:

> *What is the Grade 9 learners' understanding of electric circuit concepts after the topic has been taught as revealed in a diagnostic test on electric circuits?*

Information from both data sets (as for the two components of PCK mentioned above) was compared to establish connections between the representations teachers used as part of their enacted PCK and how these informed the Grade 9's conceptual understanding of electric circuits. This information aided in answering secondary Research Question 3:

> *How can the Grade 9 learners' understanding of the concepts be linked to the representations that the teacher used?*

By analysing the data through the lens of the three secondary research questions, the primary research question is ultimately addressed, thereby fulfilling the core objective of the study:

> *How do teachers use and present representations, as a display of their enacted PCK, to inform Grade 9 learners' understanding of concepts in electric circuits?*

6.3 Answering the Research Questions

The study set out to investigate the link between teachers' use of representations and learners' conceptual understanding of electric circuits by answering the following research questions:

6.3.1 Secondary Research Question 1

How do the teachers enact their PCK, as revealed in their lesson planning and reflections during interviews regarding the use of their representations to teach concepts in electric circuits to Grade 9 learners?

In an early paper that conceptualised PCK and illustrated how PCK applies to teachers in science education, Magnusson et al. (1999) concluded that while teachers may have varying levels of PCK across different components, mastering a single component is insufficient for effective teaching. In a later study, Park and Oliver (2009) recognised the need for teachers to develop their knowledge of learner understanding of science by accessing prior knowledge, determining what learners find difficult to understand, and identifying concepts that need to be challenged. It is the integration of these components, not necessarily in equal parts, that enhances teacher effectiveness. In a similar way, the current study demonstrated that the quality of teachers' PCK differed across the various components and representations used to teach electric circuits. The following sections explore how each teacher's use of representations reflects the quality of the relevant knowledge components of their PCK.

6.3.1.1 Knowledge of Learners' Understanding of Science

Accessing learner prior knowledge

All the teachers demonstrated a concrete understanding of the preconceptual knowledge that their learners had at the start of this teaching period. They were aware of their learners' prior knowledge before beginning instruction. Teacher A assessed prior knowledge of electric circuits by questioning learners and recognised that while they were familiar with current and ammeters, they had limited knowledge of voltage. Similarly, Teacher B and Teacher C reviewed the fundamentals of electric circuits to gauge their learners' understanding and current knowledge. Teacher B used this prior knowledge as the foundation for subsequent lessons. The same strategy was noted by Shing et al. (2018) who asserted that a well-planned lesson "takes into consideration learners' characteristics such as their prior knowledge and ability, hence leading to meaningful and effective learning" (p. 44).

Knowledge of learners' misconceptions

During the interview, the teachers were not explicitly asked to identify specific misconceptions that they thought their learners possessed. Instead, teachers were asked to identify concepts that they knew their learners found difficult to understand. The three teachers all noted that their learners struggled to understand the quantitative nature of voltage in series and parallel circuits, despite the teachers using various representations to assist them. Learners' ideas, regardless of whether they are correct or incorrect, can serve as a starting point for further teaching. However, as asserted by Gaigher (2014), it is crucial for teachers to be aware of the concepts that their learners find challenging so that they can design and select appropriate teaching approaches. In this study, the teachers expressed confidence in their ability to identify the areas where their learners struggled.

6.3.1.2 Curricular Saliency and Content Knowledge

Teacher knowledge about the place of the topic in the curriculum

In a topic-specific PCK rubric, Pitjeng (2014) described that a teacher who demonstrates exemplary PCK in the category of content sequencing is able to "(provide) reasons for the importance of the topic (that) include sequential scaffolding or development of understanding". In this study, the PCK quality of each teacher for the content sequencing component varied. While some teachers showed a strong ability to justify the order in which concepts should be taught, they struggled with justifying the order of other concepts. For instance, Teacher A believed that her learners only needed to grasp the quantitative nature of voltage as per the CAPS curriculum (Department of Basic Education, 2011a). Therefore, she taught it accordingly and planned to introduce the qualitative aspects of voltage in their senior years. This demonstrated her ability to justify the sequence in which topics or ideas related to voltage should be taught. However, she also used electrolysis and the standard reduction potentials table to introduce voltage as an energy concept. Despite this, she admitted that her learners did not understand this concept, indicating a need for better alignment with the curriculum. Teacher B and Teacher C intentionally omitted concepts such as conventional current, recognising that these could be confusing and were unnecessary at learners' current level. This selective approach reflects strong PCK, as they are aware of what would cause their learners to struggle. Conversely, Teacher C's analogy of water flow relating to speed, which is more suitable for introducing the concept of velocity to Grade 10 learners, seemed misplaced, indicating a limitation in his PCK for this particular aspect.

Content knowledge

In a recent study conducted by Schiering et al. (2023) to explore the relationship between preservice physics teachers' content knowledge, teaching experience, beliefs, and their proficiency levels of PCK, they highlighted that content knowledge has a direct influence on a teachers' PCK and use of selected teaching approaches. In the current study, this was evident in the way that teachers either employed certain strategies or consciously chose to avoid them altogether based on their content knowledge of a specific concept. For example, Teacher C demonstrated a strong understanding of the origin of conventional current but deliberately opted not to teach this concept to his learners, recognising it as too conceptually challenging. However, Teacher A utilised her knowledge of cells and the energy within them to create analogies, such as the people-charge and shop analogies, to help learners comprehend how energy is distributed throughout a circuit, despite some aspects of the analogies not fully facilitating effective conceptual understanding. This indicates that the teachers' content knowledge of specific concepts in electric circuits significantly influenced their choice of instructional approaches, thereby reflecting their PCK.

6.3.1.3 Conceptual Teaching Strategies and Representations

Selection of representations based on what learners find difficult to understand

During the interview, Teacher A identified two concepts that her learners consistently struggle with based on her recent and past teaching experience. The first is understanding voltage as an energy concept and the second is understanding how the resistance of resistors in parallel decreases total resistance instead of increasing it. To address these difficulties, she used two analogies, one for each of these challenging ideas.

Teacher C also used analogies in his teaching, though for different concepts than Teacher A. The first analogy was used to explain current flow through series circuits, while the second was used to explain current flow in parallel circuits, and the third to illustrate the relationship between current, voltage, and resistance in a circuit.

The value of using analogies in science teaching is widely recognised (Dagher, 1995). The way that teachers strived to make content more accessible demonstrated their strong PCK. However, this is only effective if they apply these approaches correctly and understand the limitations of the analogies, explaining them when necessary. However, as discussed in the following section, analogies are fluid (Dagher, 1995) and can be interpreted in various ways, which can sometimes hinder learners' understanding.

Inability to recognise the limitations of their representations

The inability to recognise the limitation of representations was unfortunately common to all teachers. Each teacher, at some point in their teaching, used a representation with limitations that had to be explained to learners for maximum understanding. As displayed in Table 6.1, Teacher A used a variety of representations, but each had its own limitations. For example, describing the process of energy transformation through components in a circuit as "used up" could lead to learners conceptualising energy as something that can disappear over time. This highlights the need to develop the teachers' PCK regarding their use of representations. This finding is significant because there is evidence to suggest that not discussing these limitations can cause misunderstandings among learners regarding the concepts being taught. During the interviews, none of the teachers acknowledged the weaknesses of their representations or discussed these limitations with their learners, which further stresses the need for improvement in their PCK. Table 6.1 summarises the representations used by the teachers and their limitations.

Table 6.1 – Limitations of representations used by Teachers A, B, and C

Teacher A	Teacher B	Teacher C
Direction of colour used through circuit path indicated conventional current without adequate explanation.	Worksheet 1 described resistors in parallel as being connected "side by side".	Water flow analogy failed to effectively illustrate the function of voltage in the circuit, leading to confusion.
Analogy 1 described energy being "used up" instead of converted or transformed through components in a circuit.	The sequence in which worksheets on current and voltage was presented blurred the distinction between these concepts.	
Analogy 2 described current as speed of electrons and more resistors connected in parallel mean more charges in the circuit.	Presentation of resistors in parallel was unclear, causing learners to miss the point.	
Voltages of branches in parallel "add up to" voltage of the cell.		

It is clear that every teacher's CTS involved employing varying levels of PCK, with some being more proficient than others when using representations.

6.3.2 Secondary Research Question 2

What is the Grade 9 learners' understanding of electric circuit concepts after the topic has been taught as revealed in a diagnostic test on electric circuits?

For learners in both South Africa and Australia, similarities emerged in their understanding and misunderstandings of concepts in electric circuits. Most learners grasped the concept of current as the flow of electricity and its behaviour in series and parallel circuits, as indicated by their highest scores on items related to current in the diagnostic test. This understanding is consistent with the observation by Burde and Wilhelm (2020) that many curricula introduce electric circuits through the lens of current before addressing voltage. As a result, learners find current easier to understand than voltage.

The item that proved the most challenging was the effect of resistors connected in parallel. Many learners showed a limited understanding or incorrect knowledge by selecting an answer that revealed their misconception. This specific misconception, with learners believing that resistance decreases the more resistors are added in parallel, was documented by Sencar and Eryilmaz (2004).

Furthermore, all learners expressed confusion between current and voltage, which is reflected in their reasonings provided for selecting certain options. In their responses to various items, learners frequently reasoned in terms of current and resistance while giving little attention to voltage, suggesting that current remained their primary focus. This finding aligns with research performed by Burde and Wilhelm (2020), which noted that learners often conceptualise voltage as a property of electric current rather than as an discrete physical quantity.

6.3.3 Secondary Research Question 3

How can the Grade 9 learners' understanding of the concepts be linked to the representations that the teacher used?

The aim was to demonstrate the impact of the representations used by the teachers on the responses provided by learners in the diagnostic test. The focus was on evaluating whether these representations led to understanding or misunderstanding of the concepts being taught.

All three teachers dedicated significant instructional time to the concept of current, comparatively less time to resistance, and even less time to voltage. Teacher A used her colour-coding technique as her primary representation method throughout the teaching period, which centred around the concept of current. Teacher B began her teaching of new concepts with a worksheet that focused on current and used a traffic analogy to illustrate the relationship between current and resistance. Teacher C used two analogies for current, one for series and another for parallel circuits. Moreover, the circuit kits used in his classes exclusively explored the relationship between current and resistance.

The results of the diagnostic test revealed a good understanding of current across all teachers' classes. Furthermore, many learners referred to current in their explanations across a variety of items, indicating that the representations influenced what they retained. This highlights how the use of these representations contributed to the learners' understanding of current in electric circuits.

There was significant evidence indicating that when teachers used words incorrectly in their representations, it influenced how learners structured their responses to items. For example, one of Teacher A's PowerPoint slides on the distribution of voltage in a parallel circuit incorrectly stated: "The potential difference of each branch is equal and <u>adds up</u> to the potential difference across the battery/cell". In items of the diagnostic test related to voltage, some learners used phrases like "voltages add up to the total voltage" in their responses. This illustrates a clear link between the error in Teacher A's explanation and how it manifested in her learners' answers.

Teacher B did not discuss voltage as an energy concept in any of her representations. She described voltage as "how much force is being used to push the electrons to start to move" and even got learners to act out this pushing phenomenon during class time. Since she related voltage to a force more than to energy, none of her learners mentioned energy in their responses. This contrasts with learners of other teachers, where, in some responses, regardless of accuracy, voltage was related to a concept of energy. The fact that Teacher B's learners did not mention voltage as an energy concept indicates that Teacher B did not emphasise or explain it as such, leading her learners to not perceive it as such.

6.3.4 Primary Research Question

How do teachers use and present representations, as a display of their enacted PCK, to inform Grade 9 learners' understanding of concepts within electric circuits?

In the current study, each representation served a specific purpose and aimed to help learners grasp particular ideas, whether it was understanding a single concept or the relationships between different concepts. The effectiveness of these representations in achieving their intended goals reflects the teachers' enacted PCK. Furthermore, the study revealed a direct link between how these representations were used and how well learners understood the concepts conveyed. Whether the representation enhanced understanding or led to misunderstanding, there was a noticeable connection between the two. This finding aligns with existing literature that emphasises the relationship between teachers' enacted PCK and learner outcomes (Alonzo & Kim, 2016; Walter, 2013).

6.4 Emerging Findings

Two important findings emerged from this study. The first finding was that if teachers do not address the limitations of their representations at some point in their teaching, it may result in misconceptions. In a study that identified four main causes of misconceptions among science learners, Suprapto (2020) discussed how teachers can inadvertently contribute to the formation of misconceptions through their explanations or the materials they provide. This was clearly demonstrated in the current study, specifically with Teacher A's use of colour highlighters to trace the path of electrons through the circuit. While this method proved to be effective in helping learners visualise the movement of electrons through different components, it inadvertently led learners to misunderstand how electrons behave when encountering parallel resistors. Specifically, learners came to believe that, when faced with resistors connected in parallel, electrons always choose a single path (keeping the colour-highlighted path in mind). If every electron encounters only one resistor in its parallel path, they concluded that no matter how many resistors are added in parallel, the rate of electron flow throughout the entire circuit remains unchanged. The repeated use of this representation caused learners to overlook the fact that adding resistors in parallel decreases the total resistance and increases the rate at which electrons move through the circuit.

Teacher A's use of analogy requires clarification, which is another example of how limitations that are not addressed in teaching can lead to misunderstandings. In her people-charge analogy, she used the term "used up" to describe energy distribution in a series circuit. While this helped explain resistors as potential dividers, it also reinforced the misconception that energy is lost between points rather than being transformed into other forms. Learners echoed this misconception in their responses to voltage questions. Though it may not significantly affect Grade 9 learners at present, it could hinder their future understanding of energy transformation in circuits.

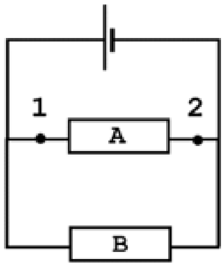
This finding concurs with Coll (2006) who emphasised that when teaching using models and analogies, it is important that educators highlight both the strengths and limitations of these tools. This will help learners better understand concepts while recognising where the models may fall short. When using models, analogies and representations, there is a risk of forming incorrect, alternative ways of thinking in learners if possible shortcomings are not specified. This is an exact consequence of inadequate use of some representations in the current study.

The second significant finding of this study is that learners often consider current and voltage as synonymous. For example, in Item 6 of the diagnostic test, seven of Teacher A's 25 learners (28%), referred only to current when explaining their choice in this item, which only referred to voltage (Figure 6-1). When the reasoning should have involved voltage across the two points remaining the same even when the bottom resistor is disconnected, some of the reasoning from the learners who selected the correct answer (Option C), included:

> *The current that will affect 1 & 2 does not flow through B.*
>
> *The current through that specific branch will remain the same as it still has only one resistor.*
>
> *They have their own current each so whatever happens to B will do nothing to 1 and 2*

Question 6

What will happen to the potential difference between points 1 and 2 if resistor B **is removed?**



A. Increase.

B. Decrease.

C. Remain the same.

Figure 6-1 – Item 6 of the diagnostic test

This finding aligns with the findings of the study conducted by Burde and Wilhelm (2020). They designed a curriculum with a focus on potential difference because learners "often struggle to understand the important relationship between current and voltage" (p. 1) and "often see voltage as a property or component of current".

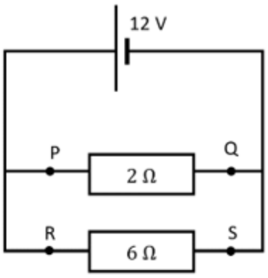
As an extension of this specific emerging finding, it was found that learners, when confronted with questions that required thinking about how two concepts related to each other (like current and voltage), their reasoning included just one of the concepts. This is evident in three of the responses of Teacher C's 14 learners (21%) who referred only to current when explaining their choice to Item 7 (Figure 6-2) in the diagnostic test that prompted a response for both current and voltage. Of the seven learners who selected the correct option (Option C), two of the responses used only resistance in their reasoning, two responses provided no valuable reasoning, and three of the responses referred to current only:

> *Because they have the same current.*
>
> *The current is affected by resistor.*
>
> *This is because the resistors are using the current and it is a parallel circuit.*

Of the 14 responses received from Teacher C's learners, only three referred to both current and voltage, irrespective of the accuracy in their reasoning.

Question 7

Read the five statements below, describing current and voltage in the circuit.



i. The current between points P and Q is greater than the current between points R and S.

ii. The current between points P and Q and points R and S is the same.

iii. The voltage between points P and Q and points R and S is both 6 V.

iv. The voltage between points P and Q and points R and S is both 12 V.

v. The voltage between points P and Q is smaller than the voltage between points R and S.

Which of the statement/s is/are correct?

A. Only ii and iii are correct.

B. Only ii and iv are correct.

C. Only i and v are correct.

D. Only i and iv are correct.

Figure 6-2 – Item 7 of the diagnostic test

This finding supports the finding made by Koponen and Huttunen (2013) who identified the ability to effectively distinguish between different concepts during the learning process as a frequent challenge in acquiring conceptual understanding in physics.

6.5 Limitations of the Study

Although the study's findings are significant, it is recommended to consider them with caution due to the research limitations relating to the diagnostic test, sample, and observations.

6.5.1 Diagnostic Test

The diagnostic test could not be validated using pre-testing and checking. However, several of the items were taken from validated sources of literature like the DIRECT test (see Annexure B).

The diagnostic test included items, like Item 7 (Figure 6-2), that required learners to address two concepts simultaneously, such as current and voltage. Upon analysis of their responses, it was revealed that learners often only addressed one concept or provided incomplete answers instead of discussing both concepts as required. Even though the value of such a question in promoting critical thinking through the integration of two different concepts is acknowledged, the item could be divided into two separate items: one asking learners to select and explain statements related to current, and the other, with the exact same diagram, focusing on voltage. This approach may have made it easier for learners to structure their thinking, address each concept individually, and reduce the likelihood of overlooking any of them. An improvement could be to scaffold the diagnostic test by placing simpler items at the beginning and more complex ones, like Item 7, towards the end.

6.5.2 Sample

Due to the researcher's relocation to Australia before data collection, the sample for this study was limited to teachers who were accessible to the researcher at the time and who had been granted permission to participate. Consequently, the study included a teacher from South Africa and two teachers from Australia. While this approach offers insights into teaching practices across different countries, it also limits the study's scope, particularly in terms of conclusions specific to South African teachers' PCK and the South African curriculum. Ideally, focusing solely on teachers in South Africa would have provided more targeted findings.

6.5.3 Observations

A teacher's actions and interactions in the classroom during instructional time provide significant insights into their level of enacted PCK, whereas their lesson planning reveals much about their personal PCK. Although interviews can offer insights into a teacher's enacted PCK and personal PCK by encouraging reflection on their actions and statements during lessons, interviews may not capture specific details, such as exact statements, learner responses, and the classroom environment. Consequently, direct observation of lessons would have been more effective in capturing these important details. This would have provided a deeper understanding of how teachers utilised their representations in class, as well as insights into learner responses, including the questions they posed. Therefore, direct observation would have offered a better understanding of their comprehension of the subject matter.

6.6 Contribution of the Study

A significant amount of research has been conducted on teaching electric circuits in high school education. Studies typically focus on learners' understanding or misconceptions of the topic (Gucluer, 2020; Helm, 1978; Nkopane et al., 2011a; Sencar & Eryilmaz, 2004), as well as various specific strategies employed by educational professionals in delivering the subject content. Some common strategies include the use of analogies (Dagher, 1995; Guerra-Ramos, 2011; Hungwe et al., 2024), simulation software (Haryadi & Pujiastuti, 2020; Ramnarain & Moosa, 2017; Ronen & Eliahu, 2000), physical circuit kits (Jaakkola et al., 2011; Reisslein et al., 2012), and inquiry-based learning (Aboagye et al., 2018; Afra et al., 2009; Mutlu, 2020; Preston, 2019). Most research on teaching strategies focuses on their ability to improve learner understanding of concepts. However, little attention is given to how the incorrect application of these strategies could have a lasting negative impact on learners' understanding.

In a related manner, it is rare for science educators to rely on a single representation, including tools or methods used to demonstrate, model, or explain scientific concepts or processes, or teaching strategy when covering a specific topic in science education. Instead, it is likely that teachers use multiple representations when teaching a particular section of material (Victoria State Government, 2020). Where teachers rely solely on a textbook to teach, they still use different representations presented in the book, like words, equations, and diagrams. This is particularly true in the topic of electric circuits, where teachers often use a combination of representations. For instance, they may utilise an animated image to illustrate the flow of current through a closed circuit, followed by a simulation or the use of physical circuit kits to explore Kirchhoff's current law in series and parallel circuits, and then conclude with an analogy to integrate the concepts of current, voltage, and resistance in an electric circuit.

This combined use of representations was demonstrated by all three teachers in this research study. This is where the study finds its value. Instead of exploring the use of a single representation by teachers to teach one or more ideas in the topic of electric circuits, the study investigated what *representations* teachers are currently using, why they believe these representations are effective in informing their learners' understanding, and what kind of effect these representations have on learners' understanding of the ideas taught through the representation.

Another valuable finding of this study is the potential disconnect between how teachers present information and how learners perceive it. Teachers might intend for a representation to highlight a particular concept, but learners may not always understand it in the intended way. For example, teachers often incorporate diagrams as a representation into their teaching, believing that these visuals will enhance learners' understanding (Preston, 2019). According to Nkopane et al. (2011a), one significant cause of misconceptions in learner understanding is the pre-existing knowledge they use as a foundation on which to build new concepts and ideas. If this foundation is flawed, which is extremely difficult to identify in all learners before the use of every representation, there is no guarantee that learners will interpret diagrams the way that the teacher intended. The current study highlights that despite teachers' best intentions in selecting representations, these tools may not always facilitate the understanding they aim to achieve. In fact, learners may unconsciously be using these representations to formulate ideas that are not accurate.

Burde et al. (2021) emphasised the limitations of using analogies as representations in science education. They caution that analogies can lead to misunderstandings if learners are not sufficiently familiar with the source domain or if certain aspects of the source domain do not apply to the target domain. In the same way, it is important that teachers make their learners aware of both the strengths and limitations of their representations to prevent misinterpretation of the concepts being taught. Thus, this research confirms that there is a significant gap in understanding how different representations not only influence learner comprehension but could also simultaneously lead to misconceptions. The study emphasises the importance of carefully selecting and using representations when teaching electric circuits. It also highlights the need for teachers to be mindful of their choice of words and instructions as these factors directly affect learners' understanding.

As a final point, this study holds practical significance in enhancing the quality of education provided by teachers to learners. Additionally, it contributes to the development of the preservice teacher education curriculum and in-service teacher workshops.

6.7 Recommendations and Suggestions

While acknowledging the listed limitations of the study, the findings still offer valuable insights from which several recommendations for research and practice can be made.

Electric circuits will likely remain a challenging concept for learners due to their abstract nature unless there are advancements that allow us to visualise electron movement. Therefore, further research should continue to focus on developing effective strategies for introducing fundamental concepts in electric circuits and preventing the formation of misconceptions, especially with the availability of new advancements in educational tools. Additional research is needed to study the effects of teachers using representations, particularly analogies, incorrectly. Specifically, an empirical study is recommended to investigate the difference between teachers who use analogies without explaining their limitations and those who explicitly state these limitations to their learners.

This study found that teachers often unintentionally create misconceptions or alternative understandings in their learners by not fully recognising the weaknesses of the visuals and representations they use. This insight could inform both preservice teacher education and in-service professional development, encouraging educators to carefully consider the strengths and weaknesses of the representations they employ.

Finally, this study emphasises a valuable opportunity for further research: exploring how the use of diagnostic tests, through learner responses, can help teachers reflect on their teaching practices and serve as a tool for professional development in teacher education.

6.8 Concluding Remarks and Reflection

The results of this study indicate that the representations used by teachers reveal their enacted PCK, which can inform learners' conceptual understanding of electric circuits. One of the significant findings is that the incorrect use of representations can result in learners forming misconceptions or developing alternative ways of thinking. This highlights the need for further research to investigate the implications of science teachers using instructional strategies incorrectly, especially regarding electric circuits. This result contributes to the existing body of knowledge regarding the influence of teacher PCK on learner outcomes, and confirms previous literature that affirms the concept-specific nature of PCK (Carlson et al., 2019; Mavhunga & Rollnick, 2012).

After reflecting on my research study, I have gained invaluable insights that apply to me as both an educator and a researcher. While writing, collecting, analysing and interpreting data, I have also been simultaneously reflecting on my teaching practices, identifying both areas of strength and areas that need improvement. I have become more aware of the importance of the language I use in the classroom and the need to be deliberate in selecting teaching methods and strategies that involve less of a risk of misunderstanding. Moreover, this study has deepened my knowledge and passion for the topic of electric circuits. The more I learned, the more excited I became about teaching this topic to my own learners. This enthusiasm is something that I now bring into my classroom with a renewed commitment to delivering content that is both accurate and engaging.

As a researcher, I learned a great deal about the value that lies in researching and contributing to the body of educational knowledge. I have gained so much knowledge about my profession by reading various articles and I hope to continue with educational research in the future.

To conclude, I would like to share a final thought: the very first article I read in my honours journey that developed into my MEd journey was Shulman's work, titled "Those who Understand: Knowledge Growth in Teaching". He begins with the infamous quote by George Bernard Shaw, "Those who can, do. Those who cannot, teach" (Shulman, 1986). I remember being drawn to whatever came after that quote because I was quite unsettled and my heart rate immediately increased. Surely being a teacher does not automatically make me a failure?! This journey reaffirmed my belief that not everyone can be an effective teacher. Teaching well requires a special knowledge and abilities that not everyone possesses. It is one thing to know something, but it is completely different to help someone else understand it well. The teaching profession is truly like no other, and I am privileged to be a part of it.

REFERENCES

Aboagye, G. K., Ossei-Anto, T. A., & Ampiah, J. G. (2018). Combining inquiry-based hands-on and simulation methods with cooperative learning on students' learning outcomes in electric circuits. *American Journal of Educational Research*, *6*(8), 1172–1181.

Afra, N. C., Osta, I., & Zoubeir, W. (2009). Students' alternative conceptions about electricity and effect of inquiry-based teaching strategies. *International Journal of Science and Mathematics Education*, *7*(1), 103–132.

Afribary. (2021, March 3). *What is the difference between the theoretical and the conceptual framework?* https://afribary.com/blog/5/what-is-the-difference-between-the-theoretical-and-the-conceptual-framework/#:~:text=The%20theoretical%20framework%20provides%20a,will%20have%20to%20be%20undertaken

Agyei, E., Jita, L., & Jita, T. (2024). Technology integration in science classrooms: Empowering student teachers for improved physics teaching with simulations. *Contemporary Mathematics and Science Education*, *5*(2), 1–16.

Aligo, B. L., Branzuela, R. L., Faraon, C. A. G., Gardon, J. D., & Orleans, A. V. (2021). Teaching and learning electricity: A study on students' and science teachers' common misconceptions. *Manila Journal of Science*, *14*(2021), 22–34.

Almasri, F. (2022). Simulations to teach science subjects: Connections among students' engagement, self-confidence, satisfaction, and learning styles. *Education and Information Technologies*, *27*(5), 7161–7181. https://doi.org/10.1007/s10639-022-10940-w

Alonzo, A. C., & Kim, J. (2016). Declarative and dynamic pedagogical content knowledge as elicited through two video-based interview methods. *Journal of Research in Science Teaching*, *53*(8), 1259–1286.

Australian Government. (2024). *Study Australia*. Australian Trade and Investment Commission. https://www.studyaustralia.gov.au/en

Balta, N. (2015). Development of 3-D mechanical models of electric circuits and their effect on students' understanding of electric potential difference. *European Journal of Physics Education*, *6*(1), 15–24.

Baptista, M., & Martins, I. (2023). Effect of a STEM approach on students' cognitive structures about electrical circuits. *International Journal of STEM Education*, *10*(1). https://doi.org/10.1186/s40594-022-00393-5

Barendsen, E., & Henze, I. (2019). Relating teacher PCK and teacher practice using classroom observation. *Research in Science Education*, *49*(5), 1141–1175.

Bayram-Jacobs, D., Henze, I., Evagorou, M., Shwartz, Y., Aschim, E. L., Alcaraz-Dominguez, S., Barajas, M., & Dagan, E. (2019). Science teachers' pedagogical content knowledge development during enactment of socioscientific curriculum materials. *Journal of Research in Science Teaching*, *56*(9), 1207–1233.

Beauchamp, T. (2008, January 2). The principle of beneficence in applied ethics. *Stanford Encyclopedia of Philosophy*. https://plato.stanford.edu/Entries/principle-beneficence/

Berry, A., Friedrichsen, P. J., & Loughran, J. (Eds.). (2015). *Re-examining pedagogical content knowledge in science education* (Vol. 395). Routledge.

Brown, S., & Salter, S. (2010). Analogies in science and science teaching. *Advances in Physiology Education*, *34*(4), 167–169.

Burde, J.-P., Weatherby, T. S., & Kronenberger, A. (2021). An analogical simulation for teaching electric circuits: a rationale for use in lower secondary school. *Physics Education*, *56*(5), Article 055010.

Burde, J.-P., & Wilhelm, T. (2020). Teaching electric circuits with a focus on potential differences. *Physical Review Physics Education Research*, *16*(2), Article 020153. https://doi.org/10.1103/physrevphyseducres.16.020153

Carlson, J., Daehler, K. R., Alonzo, A. C., Barendsen, E., Berry, A., Borowski, A., Carpendale, J., Kam Ho Chan, K., Cooper, R., & Friedrichsen, P. (2019). The refined consensus model of pedagogical content knowledge in science education. In A. Hume, R. Cooper, A., & Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 77–94). Springer.

Carolan, J., Prain, V., & Waldrip, B. (2008). Using representations for teaching and learning in science. *Teaching Science*, *54*(1), 18–23.

Chan, K. K. H., Rollnick, M., & Gess-Newsome, J. (2019). A grand rubric for measuring science teachers' pedagogical content knowledge. In A. Hume, R. Cooper, A., & Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 253–271). Springer.

Chiu, M. H., & Lin, J. W. (2005). Promoting fourth graders' conceptual change of their understanding of electric current via multiple analogies. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *42*(4), 429–464.

Choi, K., & Chang, H. (2004). The effects of using the electric circuit model in science education to facilitate learning electricity-related concepts. *Journal of the Korean Physical Society*, *44*(6), 1341–1348.

Coetzee, M., Coetzee, C., & Gaigher, E. (2022). First-year university students' conceptual understanding of electric circuits in relation to school and personal background. *Perspectives in Education*, *40*(4), 117–134.

Cohen, R., Eylon, B., & Ganiel, U. (1983). Potential difference and current in simple electric circuits: A study of students' concepts. *American Journal of Physics*, *51*(5), 407–412.

Coll, R. K. (2006). The role of models, mental models and analogies in chemistry teaching. In P. J. Aubusson, A. G. Harrison, & S. M. Ritchie. (Eds.), *Metaphor and analogy in science education* (pp. 65–77). Springer.

Connelly, L. M. (2016). Trustworthiness in qualitative research. *Medsurg Nursing*, *25*(6), 435–436.

Cook, M. (2011). Teachers' use of visual representations in the science classroom. *Science Education International*, *22*(3), 175–184.

Dagher, Z. R. (1995). Analysis of analogies used by science teachers. *Journal of Research in Science Teaching*, *32*(3), 259–270.

Department of Basic Education. (2011a). *Curriculum and Assessment Policy Statement – Physical Science (Further Education and Training Phase Grades 10–12)*. Government Printing Works. https://www.education.gov.za/Portals/0/CD/National%20Curriculum%20Statements%20and%20Vocational/CAPS%20FET%20%20PHYSICAL%20SCIENCE%20WEB.pdf?ver=2015-01-27-154258-683

Department of Basic Education. (2011b). *Curriculum and Assessment Policy Statement (Senior Phase)*. Government Printing Works.

Department of Basic Education. (2011c). *National Curriculum Statement Grades 7–9 Natural Science*. Government Printing Works. https://www.education.gov.za/Portals/0/CD/National%20Curriculum%20Statements%20and%20Vocational/CAPS%20SP%20%20NATURAL%20SCIENCES%20GR%207-9%20%20WEB.pdf?ver=2015-01-27-160159-297

Đorić, B., Lambić, D., & Jovanović, Ž. (2021). The use of different simulations and different types of feedback and students' academic performance in physics. *Research in Science Education*, *51*(5), 1437–1457.

Engelhardt, P. V., & Beichner, R. J. (2004). Students' understanding of direct current resistive electrical circuits. *American Journal of Physics*, *72*(1), 98–115. https://doi.org/10.1119/1.1614813

Espera, A. H., & Pitterson, N. P. (2019, June 15–19). *Teaching circuit concepts using evidence-based instructional approaches: A systematic review*. 2019 ASEE Annual Conference & Exposition.

Ferri, B. H., Ferri, A. A., Majerich, D. M., & Madden, A. G. (2016). Effects of in-class hands-on laboratories in a large enrollment, multiple section blended linear circuits course. *Advances in Engineering Education*, *5*(3), 1–27.

Gadzikwa, R. (2018). *Exploring the effects of computer simulations in developing conceptual understanding of Grade 10 learners in direct current circuits* [Master's thesis, University of KwaZulu-Natal].

Gaigher, E. (2014). Questions about answers: Probing teachers' awareness and planned remediation of learners' misconceptions about electric circuits. *African Journal of Research in Mathematics, Science and Technology Education*, *18*(2), 176–187.

Gentner, D., & Gentner, D. R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (p. 99–129). Lawrence Erlbaum Associates.

Gess-Newsome, J. (1999). Pedagogical content knowledge: An introduction and orientation. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge: The construct and its implications for science education* (pp. 3–17). Springer.

Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research: interviews and focus groups. *British Dental Journal*, *204*(6), 291–295. https://doi.org/10.1038/bdj.2008.192

Gooding, J., & Metz, B. (2011). From misconceptions to conceptual change. *The Science Teacher*, *78*(4), 34.

Gottschlich, B., Burde, J., Wilhelm, T., Dopatka, L., Spatz, V., Schubatzky, T., Haagen-Schützenhöfer, C., Ivanjek, L., & Hopf, M. (2024). A context-based teaching concept on electric circuits-development and first results. *Journal of Physics: Conference Series*, *2750*(1), Article 012010.

Grossman, P. L. (1990). The making of a teacher: Teacher knowledge and teacher education. *Teachers College of Columbia*.

Grover, V. (2015). Research approach: An overview. *Golden Research Thoughts*, *4*(8), 1–8.

Gucluer, Ö. C. (2020). A study on 7 grade students' misconceptions on the unit of "simple electric circuits". *International Education and Research Journal*, 49.

Guerra-Ramos, M. T. (2011). Analogies as tools for meaning making in elementary science education: How do they work in classroom settings? *Eurasia Journal of Mathematics, Science and Technology Education*, *7*(1), 29–39.

Hancock, D. R., Algozzine, B., & Lim, J. H. (2021). *Doing case study research: A practical guide for beginning researchers*. Teachers College Press.

Haryadi, R., & Pujiastuti, H. (2020). PhET simulation software-based learning to improve science process skills. *Journal of Physics: Conference Series*, *1521*, Article: 022017.

Heale, R., & Twycross, A. (2015). Validity and reliability in quantitative studies. *Evidence Based Nursing*, *18*(3), 66–67. https://doi.org/10.1136/eb-2015-102129

Helm, H. (1978). Misconceptions about physical concepts among South Africa pupils studying physical science. *South African Journal of Science*, *74*(8), 281.

Hermawati, T. (2022). Analysing science teachers' difficulties in teaching the concept of electricity in junior high school. *Research in Physics Education*, *1*(1), 33–44.

Hesti, R. (2022). Development of SKORLP four tier test form diagnostic test instruments to identify conception profiles of parallel electrical circuits. *Konstan – Jurnal Fisika dan Pendidikan Fisika*, *7*(1), 53–66. https://doi.org/10.20414/konstan.v7i1.138

Hungwe, A., Nyandoro, P., & Madzudzo, A. (2024). Developing the culturally relevant analogies to enhance the teaching and learning of electricity and DC circuits in high school physics. *Indiana Journal of Arts & Literature*, *5*(2), 30–37.

Hunziker, S., & Blankenagel, M. (2024). Multiple case research design. In Research Design in Business and Management: A Practical Guide for Students and Researchers (pp. 171-186). Springer.

Hurrell, D. (2021). Conceptual knowledge or procedural knowledge or conceptual knowledge and procedural knowledge: Why the conjunction is important to teachers. *Australian Journal of Teacher Education (Online)*, *46*(2), 57–71.

Isbah, H., & Adi, B. S. (2024). The influence of the problem based learning (PBL) learning model assisted by PhET simulation media to increase HOTS of Class 6 elementary school students in electrical circuits. *Jurnal Penelitian Pendidikan IPA*, *10*(4), 1847–1854. https://doi.org/10.29303/jppipa.v10i4.6225

Jaakkola, T., Nurmi, S., & Veermans, K. (2011). A comparison of students' conceptual understanding of electric circuits in simulation only and simulation-laboratory contexts. *Journal of Research in Science Teaching*, *48*(1), 71–93.

Jaakkola, T., & Veermans, K. (2020). Learning electric circuit principles in a simulation environment with a single representation versus "concreteness fading" through multiple representations. *Computers & Education*, *148*, Article 103811.

Jamshed, S. (2014). Qualitative research method-interviewing and observation. *Journal of Basic and Clinical Pharmacy*, *5*(4), 87. https://doi.org/10.4103/0976-0105.141942

Johnson, L. (2020, December 15). The definition of a simple circuit. *Sciencing*. https://sciencing.com/definition-simple-electrical-series-circuit-8742916.html

Kapici, H. O., Akcay, H., & De Jong, T. (2019). Using hands-on and virtual laboratories alone or together—which works better for acquiring knowledge and skills? *Journal of Science Education and Technology*, *28*, 231–250. https://doi.org/10.1007/s10956-018-9762-0

Kivunja, C. (2018). Distinguishing between theory, theoretical framework, and conceptual framework: A systematic review of lessons from the field. *International Journal of Higher Education*, *7*(6), 44–53.

Kivunja, C., & Kuyini, A. B. (2017). Understanding and applying research paradigms in educational contexts. *International Journal of Higher Education*, *6*(5), 26–41.

Koponen, I. T., & Huttunen, L. (2013). Concept development in learning physics: The case of electric current and voltage revisited. *Science & Education*, *22*(9), 2227–2254.

Kriek, J., & Kotoka, J. K. (2019). An exploratory study on the alignment between the different levels of the curriculum on circuit electricity. *African Journal of Research in Mathematics, Science and Technology Education*, *23*(3), 309–319.

Lehane, L., & Bertram, A. (2016). Getting to the CoRe of it: A review of a specific PCK conceptual lens in science educational research. *Educación Química*, *27*(1), 52–58.

Loughran, J., Berry, A., & Mulhall, P. (2012). *Understanding and developing science teachers' pedagogical content knowledge* (Vol. 12). Springer Science & Business Media.

Loughran, J., Mulhall, P., & Berry, A. (2004). In search of pedagogical content knowledge in science: Developing ways of articulating and documenting professional practice. *Journal of Research in Science Teaching*, *41*(4), 370–391.

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teaching. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge: The construct and its implications for science education* (pp. 95–132). Springer.

Masters, G. (2018, August 27). The role of evidence in teaching and learning. *Teacher*. https://www.teachermagazine.com/au_en/articles/the-role-of-evidence-in-teaching-and-learning

Mavhunga, M., & Rollnick, M. (2012). Development and piloting a tool for measuring topic-specific PCK in chemical equilibrium. *Proceedings of the ESERA 2011 Conference: Science Learning and Citizenship*, Lyon, France: European Science Education Research Association.

Mazibe, E. N., Coetzee, C., & Gaigher, E. (2020). A comparison between reported and enacted pedagogical content knowledge (PCK) about graphs of motion. *Research in Science Education*, *50*(10), 941–964.

Mazibe, E. N., Gaigher, E., & Coetzee, C. (2020). Comparing pedagogical content knowledge across fundamental concepts of electrostatics: A case of three pre-service teachers. *African Journal of Research in Mathematics, Science and Technology Education*, *24*(2), 143–155.

Mazibe, E. N., Gaigher, E., & Coetzee, C. (2023). Exploring dynamic pedagogical content knowledge across fundamental concepts of electrostatics. *Eurasia Journal of Mathematics, Science and Technology Education*, *19*(3), Article em2241. https://doi.org/10.29333/ejmste/13023

Mazibe, E. N., Gaigher, E., & Coetzee, C. (2024). The relationship between teachers' enacted pedagogical content knowledge and student learning in fundamental concepts of electrostatics. *Research in Science & Technological Education*, 1–19. https://doi.org/10.1080/02635143.2023.2296434

McCombes, S. (2023, September 19). *Sampling Methods | Types, Techniques & Examples*. https://www.scribbr.com/methodology/sampling-methods/

Metioui, A. (2012). Acquiring knowledge in learning concepts from electrical circuits: The use of multiple representations in technology-based learning environments. *Journal of Systemics, Cybernetics and Informatics*, *10*(2), 24–35.

Metioui, A., & Trudel, L. (2012). Acquiring knowledge in learning concepts from electrical circuits: The Use of multiple representations in technology-based learning environments. *Systemics, Cybernetics and Informatics*, *10*(2), 24–35.

Millar, R. (1991). Why is science hard to learn? *Journal of Computer Assisted Learning*, *7*(2), 66–74.

Mmekwa, K. (2023, June 9). *Is the South African basic education system in crisis?* LinkedIn. https://www.linkedin.com/pulse/south-african-basic-education-system-crisis-dr-kgabo-mmekwa/

Moodley, K., & Gaigher, E. (2019). Teaching electric circuits: Teachers' perceptions and learners' misconceptions. *Research in Science Education*, *49*(1), 73–89. https://doi.org/10.1007/s11165-017-9615-5

Mutlu, A. (2020). Evaluation of students' scientific process skills through reflective worksheets in the inquiry-based learning environments. *Reflective Practice*, *21*(2), 271–286.

Ngwane, M. (2019). *Examining the use of multiple representations to teach vectors in Grade 10 physical sciences* [University of the Western Cape].

Nilsson, P. (2014). When teaching makes a difference: Developing science teachers' pedagogical content knowledge through learning study. *International Journal of Science Education*, *36*(11), 1794–1814.

Nkopane, L., Kriek, J., Basson, I., & Lemmer, M. (2011). Alternative conceptions about simple electric circuits amongst high school FET band learners. *Proceedings of the International Conference of Science, Mathematics and Technology Education*, Kruger Park.

NSW Education. (2018). *Science Years 7–10 Syllabus*. NSW Education Standards Authority. https://www.educationstandards.nsw.edu.au/wps/portal/nesa/k-10/learning-areas/science/science-7-10-2018

NSW Government. (2024). *NSW Curriculum*. https://curriculum.nsw.edu.au/learning-areas/science/science-7-10-2023/content/stage-5/fab404b99e

Oancea, A. E., & Punch, K. F. (2014). *Introduction to research methods in education*. SAGE.

Ogegbo, A. A., Gaigher, E., & Salagaram, T. (2019). Benefits and challenges of lesson study: A case of teaching Physical Sciences in South Africa. *South African Journal of Education*, *39*(1), 1–9. https://doi.org/10.15700/saje.v39n1a1680

Oliveira, H., & Bonito, J. (2023). Practical work in science education: A systematic literature review. *Frontiers in Education*, *8*. https://doi.org/10.3389/feduc.2023.1151641

Önder, F., Senyigit, Ç., & Silay, I. (2017). The effects of misconceptions on pre-service teachers' ability to constructing simple electric circuits. *European Journal of Physics Education*, *8*(1), 1–10.

Park, S., & Chen, Y. C. (2012). Mapping out the integration of the components of pedagogical content knowledge (PCK): Examples from high school biology classrooms. *Journal of Research in Science Teaching*, *49*(7), 922–941.

Park, S., & Oliver, J. (2009). The translation of teachers' understanding of gifted students into instructional strategies for teaching science. *Journal of Science Teacher Education*, *20*(4), 333–351.

Pastore, J. (2024, February 17). *10 Evidence-based instructional strategies for the classroom*. ClickView. https://www.clickvieweducation.com/blog/teaching-strategies/evidence-based-instructional-strategies

Pitjeng, R. J. (2014). *Investigating the effect of an intervention on novice science teachers topic specific pedagogical content knowledge* [Doctoral thesis, University of the Witwatersrand].

Ponelis, S. R. (2015). Using interpretive qualitative case studies for exploratory research in doctoral studies: A case of information systems research in small and medium enterprises. *International Journal of Doctoral Studies*, *10*, 535.

Poti, J. G., Dudu, W. T., & Sebatana, M. J. (2022). A South African beginner natural sciences teacher's articulated PCK-in-practice with respect to electric circuits: A case study. *Eurasia Journal of Mathematics, Science and Technology Education*, *18*(10), Article em2161.

Preston, C., Hubber, P., Bondurant-Scott, M., & Gunesekere, I. (2020). A representation construction approach to learning about electrical energy in year 6. *Teaching Science*, *66*(2), 5–19.

Preston, C. M. (2019). Effect of a diagram on primary students' understanding about electric circuits. *Research in Science Education*, *49*(3), 1433–1456.

Ramnarain, U., & Hlatswayo, M. (2018). Teacher beliefs and attitudes about inquiry-based learning in a rural school district in South Africa. *South African Journal of Education*, *38*(1), 1–10. https://doi.org/10.15700/saje.v38n1a1431

Ramnarain, U., & Moosa, S. (2017). The use of simulations in correcting electricity misconceptions of grade 10 South African physical sciences learners. *International Journal of Innovation in Science and Mathematics Education*, *25*(5), 1–20.

Reisslein, J., Johnson, A. M., & Reisslein, M. (2014). Color coding of circuit quantities in introductory circuit analysis instruction. *IEEE Transactions on Education*, *58*(1), 7–14.

Reisslein, J., Ozogul, G., Johnson, A. M., Bishop, K. L., Harvey, J., & Reisslein, M. (2012). Circuits kit K–12 outreach: Impact of circuit element representation and student gender. *IEEE Transactions on Education*, *56*(3), 316–321.

Ronen, M., & Eliahu, M. (2000). Simulation—A bridge between theory and reality: The case of electric circuits. *Journal of Computer Assisted Learning*, *16*(1), 14–26.

Saunders, M., & Tosey, P. (2012). The layers of research design rapport. *Rapport*, (Winter), 58–59.

Schiering, D., Sorge, S., Keller, M. M., & Neumann, K. (2023). A proficiency model for pre-service physics teachers' pedagogical content knowledge (PCK): What constitutes high-level PCK? *Journal of Research in Science Teaching*, *60*(1), 136–163. https://doi.org/10.1002/tea.21793

Sencar, S., & Eryilmaz, A. (2004). Factors mediating the effect of gender on ninth-grade Turkish students' misconceptions concerning electric circuits. *Journal of Research in Science Teaching*, *41*(6), 603–616. https://doi.org/10.1002/tea.20016

Shelley, M., & Kiray, S. A. (Eds.). (2018). *Research highlights in STEM education*. ISRES.

Shing, C. L., Saat, R. M., & Loke, S. H. (2018). The knowledge of teaching pedagogical content knowledge (PCK). *MOJES: Malaysian Online Journal of Educational Sciences*, *3*(3), 40–55.

Shipstone, D. (1984). A study of children's understanding of electricity in simple DC circuits. *European Journal of Science Education*, *6*(2), 185–198.

Shirazi, S. (2017). Student experience of school science. *International Journal of Science Education*, *39*(14), 1891–1912. https://doi.org/10.1080/09500693.2017.1356943

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher*, *15*(2), 4–14.

South Africa's education system in crisis. (2022, October 15). *BusinessTech*. https://businesstech.co.za/news/business/634271/south-africas-education-system-in-crisis/

Sullivan-Clarke, A. (2019). Misled by metaphor: The problem of ingrained analogy. *Perspectives on Science*, *27*(2), 153–170. https://doi.org/10.1162/posc_a_00303

Summer, R. (2023, April 20). South African children's grim prospects in a failing education system. *Mail & Guardian.* https://mg.co.za/thought-leader/opinion/2023-04-20-south-african-childrens-grim-prospects-in-a-failing-education-system/

Suprapto, N. (2020). Do we experience misconceptions?: An ontological review of misconceptions in science. *Studies in Philosophy of Science and Education*, *1*(2), 50–55.

Taylor, P. C., & Medina, M. N. (2019). Teaching and learning transformative research: Complexity, challenge and change. In B. C. Luitel & P. C. S. Taylor (Eds.), *Research as transformative learning for sustainable futures* (pp. 39–57). Brill.

Tenny, B. J., & Brannan, G. D. (2022). *Qualitative study*. StatPearls. https://www.ncbi.nlm.nih.gov/books/NBK470395/

Van Gend, I. (2023, November 6). STEM subjects are key to getting South Africa's youth employed. *George Herald*. https://www.georgeherald.com/News/Article/LifeStyle/stem-subjects-are-key-to-getting-south-africa-s-youth-employed-202311061211

Veal, W. R., & MaKinster, J. G. (1999). Pedagogical content knowledge taxonomies. *The Electronic Journal for Research in Science & Mathematics Education*, *3*(4).

Victoria State Government. (2020). *High impact teaching strategies.* Department of Education and Training. https://www.education.vic.gov.au/Documents/school/teachers/support/high-impact-teaching-strategies.pdf

Villarino, G. N. B. (2018). Students' alternative conceptions and patterns of understanding on electric circuits. *International Journal of Innovation in Science and Mathematics Education*, *26*(4), 49–70.

Walter, E. M. (2013). *The influence of pedagogical content knowledge (PCK) for teaching macroevolution on student outcomes in a general education biology course* [Doctoral thesis, University of Missouri, Columbia].

Webb, P. (1992). Primary science teachers' understandings of electric current. *International Journal of Science Education*, *14*(4), 423–429.

Williamson, K., Given, L., & Scifleet, P. (2013). Qualitative data analysis. In K. Williamson & G. Johanson (Eds.), *Research methods: Information, systems, and contexts* (pp. 417–439). Tilde University Press.

Yang, E.-M., Greenbowe, T., & Andre, T. (2004). The effective use of an interactive software program to reduce students' misconceptions about batteries. *Journal of Chemical Education*, *81*(4), 587.

Zaitsev, I. V. (2021). Conjunctional Concepts: The Conceptual Teaching Technique in Biology Classes. *Journal of Microbiology & Biology Education*, *22*(3), Article e00168-21. https://doi.org/10.1128/jmbe.00168-21

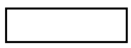
ANNEXURE A – DIAGNOSTIC TEST

GRADE 9 DIAGNOSTIC TEST: ELECTRICAL CIRCUITS

Name: ____

Instructions:

1. Various possible answers are suggested for the following questions. Indicate your answer by circling the correct letter of your choice.
2. Where requested, provide a brief explanation for your answer in the space provided.
3. All light bulbs, resistors, and cells should be considered identical unless otherwise indicated. The internal resistance of the battery and the resistance offered by the conducting wires can be ignored.
4. A key to the symbols used in this test is provided below:

	Light bulb		Conducting wire
	Cell		Resistor

---

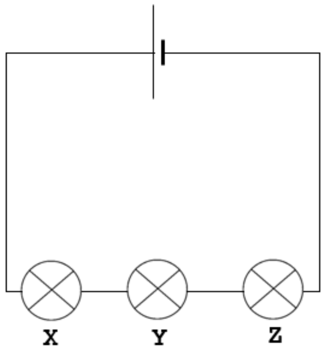
Question 1

Why do the lights in your house come on instantaneously when you put on the switch?

A. Energy travels to the lights immediately and is released.
B. The circuits in our homes are wired in parallel. Thus, current is already flowing.
C. Charges in the wire travel very fast.
D. Charges are already in the wire. When the circuit is completed, the charges begin moving from where they are in the wires.

Question 2

Light bulb Y blows out. What will happen to the **other light bulbs** in the circuit?



A. Light bulb X and Z will continue to shine.

B. Only light bulb X will shine.

C. None of the light bulbs will shine.

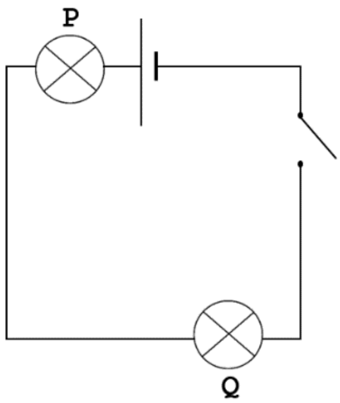
Explanation: ____

____

____

Question 3

In the circuit below, all the bulbs are identical. Compare the brightness of the light bulbs the moment that the switch is closed.



A. P is the brightest and Q is the dimmest and P shines before Q does.

B. P is the brightest and Q is the dimmest, and both light bulbs light up at the same time.

C. P and Q have the same brightness and both light bulbs light up at the same time.

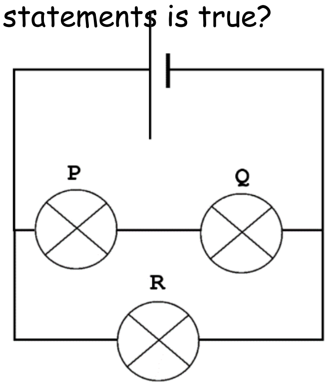
Explanation:: ____

____

____

Question 4

In the circuit below, all the light bulbs are identical. Which one of the following statements is true?



A. The current in P is greater than the current in Q.

B. The current in P is greater than the current in R.

C. The current in P is the same as the current in Q.

D. The current in P is the same as in Q and as in R.

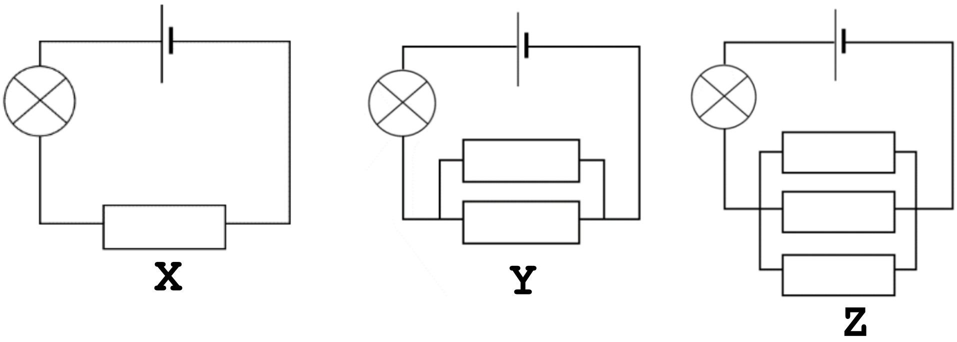
Explanation: ____

____

____

Question 5

In which circuit would the light bulb shine the dimmest?



A. Circuit X.

B. Circuit Y.

C. Circuit Z.

D. The light bulb will shine with the same brightness in all three circuits.

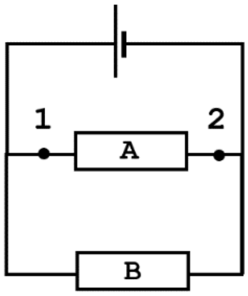
Explanation: ____

____

____

Question 6

What will happen to the potential difference between points 1 and 2 if resistor B **is removed**?



A. Increase.

B. Decrease.

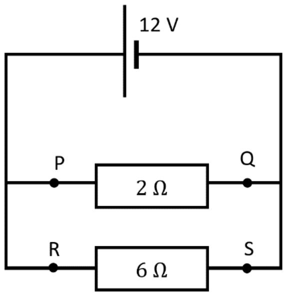
C. Remain the same.

Explanation: ____

____

Question 7

Read the five statements below, describing current and voltage in the circuit.



i. *The current between points P and Q is greater than current between points R and S.*

ii. *The current between points P and Q and points R and S is the same.*

iii. *The voltage between points P and Q and points R and S is both 6 V.*

iv. *The voltage between points P and Q and points R and S is both 12 V.*

v. *The voltage between points P and Q is smaller than the voltage between R and S.*

Which of the statement/s is/are correct?

A. Only ii and iii are correct.

B. Only ii and iv are correct.

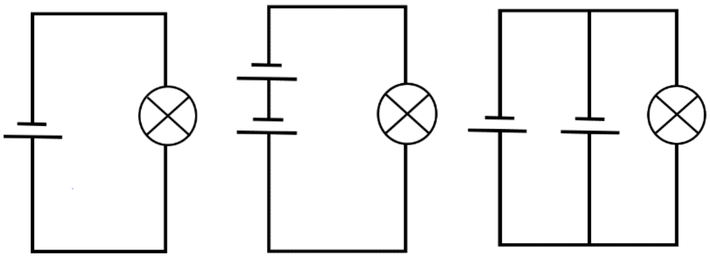
C. Only i and v are correct.

D. Only i and iv are correct.

Explanation: ____

Question 8

Compare the brightness of the light bulb in circuit 1, 2 and 3.



A. The brightness is the same in all three circuits.

B. Brightness in 1 and 3 is the same, but dimmer than 2.

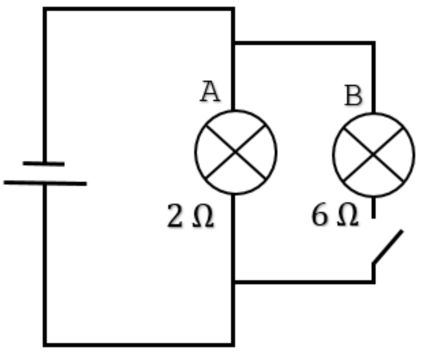
C. Brightness in 2 and 3 is the same, and brighter than 1.

D. Circuit 2 is brightest, then 3, then 1 being the dimmest.

Explanation: ____

Question 9

Consider the circuit below, with two bulbs A and B with resistances as indicated in the diagram. Select the statement below that is true.



A. When the switch is closed, light bulb A will not shine.

B. If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would no longer shine.

C. If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would still shine but slightly dimmer.

D. If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would still shine with the same brightness.

Explanation: ____

Question 10

A cell becomes 'flat' because...

i. all of its charges have been used up.

ii. the chemical reaction in the cell no longer takes place.

iii. the cell cannot convert chemical energy into electrical energy anymore.

iv. the charges can no longer move out of the battery.

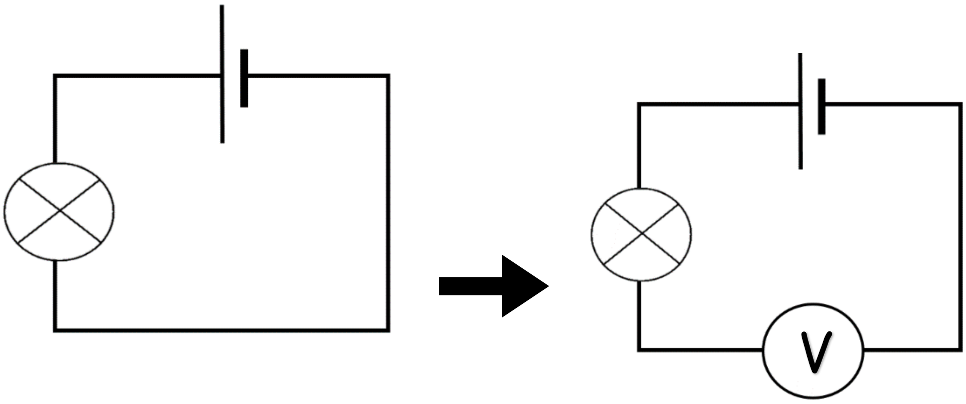
A. Only i and iv are true.

B. Only ii and iii are true.

C. ii, iii and iv are true.

Question 11

A voltmeter is connected in series to the circuit below.



What effect will this have on the brightness of the light bulb?

A. Increase.

B. Decrease.

C. Remain the same.

D. The light bulb will no longer shine.

Explanation: ____

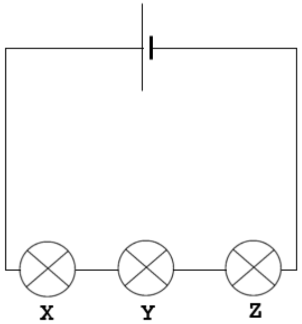
____

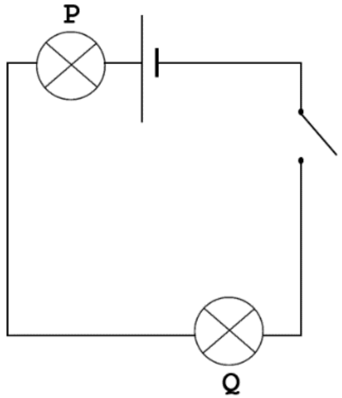
END OF TEST

ANNEXURE B – ANALYSIS OF DIAGNOSTIC TEST

Question	Topic
1	Origin of charges
2	Current flow in series circuits
3	Current flow in series circuits
4	Current flow in series and parallel circuits
5	Current flow in parallel circuits
6	Voltage in parallel circuits
7	Relationship between current and voltage in parallel circuits
8	Cell as a system of electrical energy
9	Short circuit understanding
10	Cell as a system of electrical energy
11	Connection of voltmeters

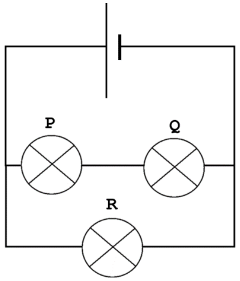
QUESTION 1		Assessed concept: Origin of charges	
Why do the lights in your house come on instantaneously when you put on the switch?		Source:	Question 11 DIRECT. (Engelhardt and Beichner (2004))
		Topic covered according to CAPS document:	“Cells are a source of electricity.” (Department of Basic Education, 2011c, p. 74) “Potential and kinetic energy are involved in…electrical systems.” (Department of Basic Education, 2011c, p. 26) “The lighting system in our homes is usually connected in parallel. If one light bulb fuses (filament breaks), the rest of the lights remain on because they are each connected in their own parallel pathway, to the mains circuit.” (Department of Basic Education, 2011c, p. 74)
		Answer description	
A.	Energy travels to the lights immediately and is released.	Energy travels through the circuit – not charges.	
B.	The circuits in our homes are wired in parallel. Thus, current is already flowing.	Charges move even if the circuit is not complete.	
C.	Charges in the wire travel very fast.	Charges move from the source of power to the output devices extremely quickly.	
D.	Charges are already in the wire. When the circuit is completed, the charges begin moving from where they are in the wires.	Correct answer.	

<table>
<tr><th colspan="2">QUESTION 2</th><th colspan="2">Assessed concept: Current flow in series circuits</th></tr>
<tr><td colspan="2" rowspan="3">Light bulb Y blows out. What will happen to the other light bulbs in the circuit?
</td><td>Source:</td><td>Own teaching experience</td></tr>
<tr><td>Topic covered according to CAPS document:</td><td>“A series circuit provides only one pathway for the current passing through it.” ((Department of Basic Education, 2011c, p. 49)</td></tr>
<tr><td colspan="2">Answer description</td></tr>
<tr><td>A.</td><td>Light bulb X and Z will continue to shine.</td><td colspan="2">Sink Model Misconception: “Students think that single wire connection allows electricity to sink from the power supply to the electrical device, thereby powering the device (Chambers & Andre, 1997, as cited in Sencar & Eryilmaz, 2004, p. 606)</td></tr>
<tr><td>B.</td><td>Only light bulb X will shine.</td><td colspan="2">Local and Sequential Reasoning Model Misconception: Students think that changes in circuits have only local effect rather than effects on the whole circuit (Cohen et al., 1983, as cited in Sencar & Eryilmaz, 2004, p. 607).</td></tr>
<tr><td>C.</td><td>None of the light bulbs will shine.</td><td colspan="2">Correct answer.</td></tr>
</table>

<table>
<tr><td colspan="2">QUESTION 3</td><td colspan="2">DESCRIPTION: Current flow in series circuits</td></tr>
<tr><td colspan="2" rowspan="3">In the circuit below, all the bulbs are identical. Compare the brightness of the light bulbs the moment that the switch is closed.

</td><td>Source:</td><td>Combination of own experience and that of other science teachers.</td></tr>
<tr><td>Topic covered according to CAPS document:</td><td>“ The current is the same everywhere in the circuit.” (Department of Basic Education, 2011c, p. 49)</td></tr>
<tr><td colspan="2">Answer Description</td></tr>
<tr><td>A.</td><td>P is the brightest and Q is the dimmest and P shines before Q does.</td><td colspan="2">Weakening Current Model Misconception: Students think that current flows in one direction around a circuit, but that the current gradually weakens because each device in the circuit uses up some of the current (Chambers & Andre, 1997; Heller & Finley, 1992, as cited in Sencar & Eryilmaz, 2004, p. 607).</td></tr>
<tr><td>B.</td><td>P is the brightest and Q is the dimmest, and both light bulbs light up at the same time.</td><td colspan="2">Since the resistors are connected in series, the current through them is the same and the light bulbs light up at the same time.

However, since light bulb P is closer to the cell than light bulb Q, P is brighter:

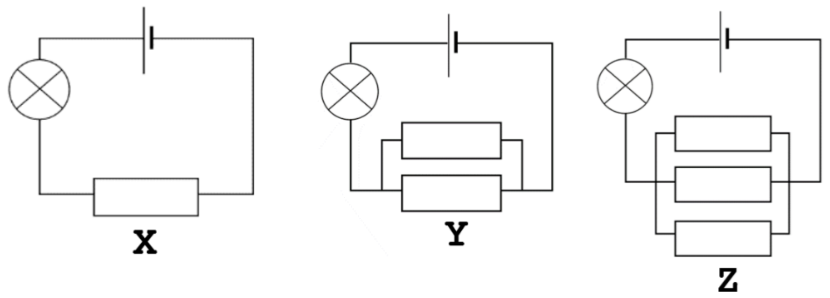
Empirical Rule Model Misconception: Students think that the further away the bulb is from the battery, the dimmer the bulb (Heller & Finley, 1992, as cited in Sencar &Eryilmaz, 2004, p. 607).</td></tr>
<tr><td>C.</td><td>P and Q have the same brightness and both light bulbs light up at the same time.</td><td colspan="2">Correct answer.</td></tr>
</table>

<table>
<tr><td colspan="2">QUESTION 4</td><td colspan="2">Assessed concept: Current flow in series and parallel circuits</td></tr>
<tr><td colspan="2" rowspan="3">In the circuit below, all the light bulbs are identical. Which one of the following statements is true?

</td><td>Source:</td><td>Combination of own experience and that of other science teachers. Related to question 17 in DIRECT. (Engelhardt & Beichner, 2004, p. 111)</td></tr>
<tr><td>Topic covered according to CAPS document:</td><td>“The current is the same when measured at any point in a given series circuit (connection).” (Department of Basic Education, 2011c, p. 74)

“ Resistors in a circuit have an influence on the amount of electric current flowing in that circuit.” (Department of Basic Education, 2011c, p. 48)

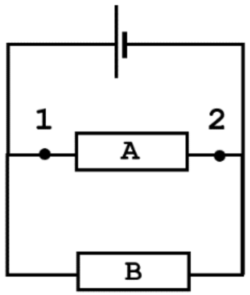
“ A parallel circuit provides two or more pathways for the current passing through it.” (Department of Basic Education, 2011c, p. 49)</td></tr>
<tr><td colspan="2">Answer description</td></tr>
<tr><td>A.</td><td>The current in P is greater than the current in Q.</td><td colspan="2">Closer to cell. Weakening Current Model Misconception: Students think that current flows in one direction around a circuit, but that the current gradually weakens because each device in the circuit uses up some of the current (Chambers & Andre, 1997; Heller & Finley, 1992, as cited in Sencar & Eryilmaz, 2004, p. 607).Empirical Rule Model Misconception: Students think that the further away the bulb is from the battery, the dimmer the bulb (Heller & Finley, 1992, as cited in Sencar &Eryilmaz, 2004, p. 607).</td></tr>
<tr><td>B.</td><td>The current in P is greater than the current in R.</td><td colspan="2">Closer to cell. Weakening Current Model Misconception: Students think that current flows in one direction around a circuit, but that the current gradually weakens because each device in the circuit uses up some of the current (Chambers & Andre, 1997; Heller & Finley, 1992, as cited in Sencar & Eryilmaz, 2004, p. 607).

Empirical Rule Model Misconception: Students think that the further away the bulb is from the battery, the dimmer the bulb (Heller & Finley, 1992, as cited in Sencar & Eryilmaz, 2004, p. 607).</td></tr>
<tr><td>D.</td><td>The current in P is the same as the current in Q.</td><td colspan="2">Correct answer.</td></tr>
<tr><td>E.</td><td>The current in P is the same as in Q and as in R.</td><td colspan="2">Current is the same regardless of the connection type. Shared Current Model: Students think that current is the same at all points in a circuit regardless of connection types and that all devices in the circuit have the same amount of current (Chambers & Andre, 1997; Heller & Finley, 1992, as cited in Sencar & Eryilmaz, 2004, pg 607).</td></tr>
</table>

<table>
<tr><th colspan="2">QUESTION 5</th><th colspan="2">Assessed concept: Current flow in parallel circuits</th></tr>
<tr><td colspan="2" rowspan="3">In which circuit would the light bulb shine the dimmest?
</td><td>Source:</td><td>Combination of own experience and that of other science teachers.

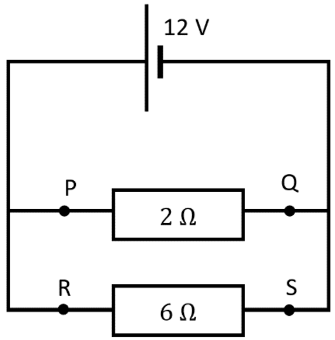
Related to question 29 in DIRECT. (Engelhardt & Beichner, 2004, p. 114)</td></tr>
<tr><td>Topic covered according to CAPS document:</td><td>“The total current in the circuit increases with each resistor added in parallel” (Department of Basic Education, 2011c, p. 74)</td></tr>
<tr><th colspan="2">Answer description</th></tr>
<tr><td>A.</td><td>Circuit X.</td><td colspan="2">Correct answer.</td></tr>
<tr><td>B.</td><td>Circuit Y.</td><td colspan="2">Distractor.</td></tr>
<tr><td>C.</td><td>Circuit Z.</td><td colspan="2">Parallel Circuit Misconception Model: Students believe that adding a resistance in a new parallel path to a circuit increases the total resistance of the circuit (Cohen et al., 1983; Dupin & Johsua, 1987, as cited in Sencar & Eryilmaz, 2004, p. 607).</td></tr>
<tr><td>D.</td><td>The light bulb will shine with the same brightness in all three circuits.</td><td colspan="2">Rule application error. Current reaches the lightbulb first. So any changes made after the lightbulb is irrelevant – this is why it shines with the same brightness regardless of the connection of the resistors that follow the light bulb.

Local and Sequential Reasoning Model: Students think that changes in circuits have only local effect rather than effects on the whole circuit (Cohen et al., 1983).</td></tr>
</table>

<table>
<tr><th colspan="2">QUESTION 6</th><th colspan="2">Assessed concept: Voltage in parallel circuits</th></tr>
<tr><td colspan="2" rowspan="3">What will happen to the potential difference between points 1 and 2 if resistor B is removed?

</td><td>Source:</td><td>Question 15 from DIRECT. (Engelhardt & Beichner, 2004, p. 111)</td></tr>
<tr><td>Topic covered according to CAPS document:</td><td>“The voltage is the same across each resistor connected in parallel.” (Department of Basic Education, 2011c, p. 74)</td></tr>
<tr><th colspan="2">Answer description</th></tr>
<tr><td>A.</td><td>Increase.</td><td colspan="2">Rule application error. Total voltage is divided between the two branches. When B is removed, total voltage is equal to voltage over resistor A – increasing.</td></tr>
<tr><td>B.</td><td>Decrease.</td><td colspan="2">Term confusion I/V. When resistor B is removed, the circuit connection becomes series, with a higher resistance and therefore a lower current.</td></tr>
<tr><td>C.</td><td>Remain the same.</td><td colspan="2">Correct answer.</td></tr>
</table>

QUESTION 7	Assessed concept: Relationship between current and voltage in parallel circuits	
	Source:	Own experience
	Topic covered according to CAPS document:	“ The voltage is the same across each resistor connected in parallel.” (Department of Basic Education, 2011c, p. 74) “ The total voltage across the battery is the same as the sum of the voltages across each of the resistors.” (Department of Basic Education, 2011c, p. 73) “ A resistor is a conducting material selected to control the current.” (Department of Basic Education, 2011c, p. 73) Relationship between resistance and current.

Read the five statements below, describing current and voltage in the circuit.



vi. The current between points P and Q is greater than the current between points R and S.
vii. The current between points P and Q and points R and S is the same.
viii. The voltage between points P and Q and points R and S is both 6 V.
ix. The voltage between points P and Q and points R and S is both 12 V.
x. The voltage between points P and Q is smaller than the voltage between points R and S.

Which of the statement/s is/are correct?

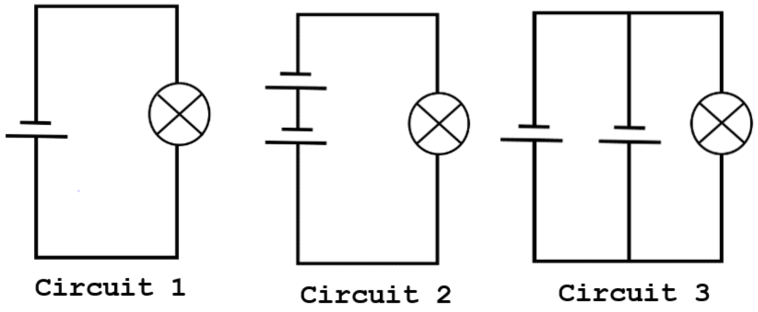
A.	Only ii and iii are correct.

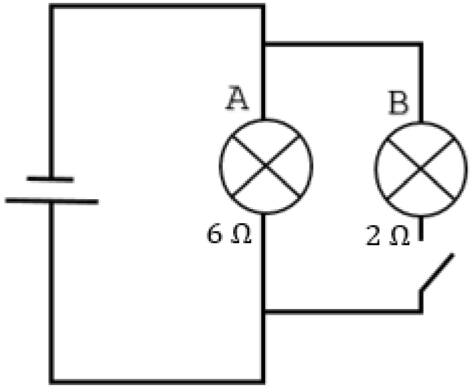
Answer Description

Rule application error:

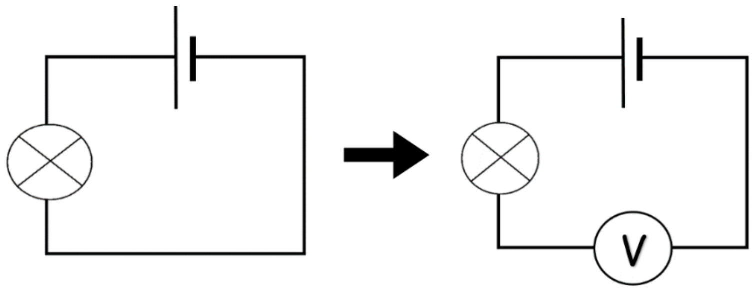
- Current is the same no matter how the resistors are connected.
- Voltage is same across resistors in parallel and is each equal to half the voltage of the cell since there are two branches – regardless of resistance of branches.
- Current incorrect. Voltage incorrect.

B.	Only ii and iv are correct.	Rule application error: • Current is the same no matter how the resistors are connected. • Voltage is same across resistors in parallel and is each equal to the voltage of the cell. • Current incorrect. Voltage correct.
C.	Only i and v are correct.	Rule application error: • Current and voltage between PQ are both smaller than RS due to the resistance between PQ being smaller than between RS. • Current correct. Voltage incorrect.
D.	Only i and iv are correct	Correct answer.

QUESTION 8		**Assessed concept: Cells as systems of electrical energy**	
Compare the brightness of the light bulb in circuit 1, 2 and 3. 		Source:	Altered but based on question 3 in DIRECT. (Engelhardt & Beichner, 2004, p. 108)
		Topic covered according to CAPS document:	“When cells (of same voltage) are connected in parallel, the voltage across them is the same as for one cell. (Department of Basic Education, 2011c, p. 74) “When cells are connected together in series, the total voltage is the sum of the voltages (potential differences) of individual cells.” (Department of Basic Education, 2011c, p. 73)
		Answer Description	
A.	The brightness is the same in all three circuits.	**Power Supply as a Constant Current Source Model**: Students think that power supply releases the same fixed amount of current to every circuit (Cohen et al., 1983; Dupin & Johsua, 1987 as cited in Sencar & Eryilmaz, 2004 p. 607).	
B.	Brightness in 1 and 3 is the same, but dimmer than 2.	Correct answer.	
C.	Brightness in 2 and 3 is the same, and brighter than 1.	Rule application error: Two cells brighter than one cell regardless of connection.	
D.	Circuit 2 is brightest, then 3, then 1 being the dimmest.	Rule application error: Two cells in series brighter than 2 cells in parallel. Brightness of bulbs is dependent on the number of cells connected – not on how the cells are connected.	

<table>
<tr><td colspan="2">QUESTION 9</td><td colspan="2">Assessed concept: Short circuit understanding.</td></tr>
<tr><td colspan="2" rowspan="2">Consider the circuit below, with two bulbs A and B with resistances as indicated in the diagram. Select the correct option below.

</td><td>Source:</td><td>Altered but based on question 19 in DIRECT. (Engelhardt & Beichner, 2004, p. 112)</td></tr>
<tr><td>Topic covered according to CAPS document:</td><td>“A short circuit can occur when an electric current takes the path of lowest resistance…” (Department of Basic Education, 2011c, p. 48)</td></tr>
<tr><td colspan="2"></td><td colspan="2">Answer Description</td></tr>
<tr><td>A.</td><td>When the switch is closed, light bulb A will not shine.</td><td colspan="2">Rule application error: “Current will follow the path of least resistance.”</td></tr>
<tr><td>B.</td><td>If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would no longer shine.</td><td colspan="2">Correct answer.</td></tr>
<tr><td>C.</td><td>If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would still shine but slightly dimmer.</td><td colspan="2">Not a complete understanding of short circuits. Indicates that learner still has doubts.</td></tr>
<tr><td>D.</td><td>If light bulb B were replaced with a copper wire and the switch was closed, light bulb A would still shine with the same brightness.</td><td colspan="2">Short Circuit Preconception Model: Students think that wire connections without devices attached to the circuit are irrelevant and can be ignored (Shipstone et al., 1988, as cited in Sencar & Eryilmaz, 2004 pg. 607).</td></tr>
</table>

QUESTION 10		Assessed concept: Cells as a system of electrical energy	
A cell becomes 'flat' because… **v. all of its charges have been used up.** **vi. the chemical reaction in the cell no longer takes place.** **vii. the cell cannot convert chemical energy into electrical energy anymore.** viii. **the charges can no longer move out of the battery.**		Source:	Own experience.
		Topic covered according to CAPS document:	"A cell is a system in which certain chemical reactions can cause the flow of electricity through an external circuit" (Department of Basic Education, 2011c, p. 73)
		Answer Description	
A.	Only i and iv are true.	The charges originate from the cell. **Sink Model Misconception**: "Students think that single wire connection allows electricity to sink from the power supply to the electrical device, thereby powering the device (Chambers & Andre, 1997, as cited in Sencar & Eryilmaz, 2004, p. 606)	
B.	Only ii and iii are true.	Correct answer.	
C.	ii, iii and iv are true.	Incorrect interpretation: The charges originate from the cell and cannot move out of the cell because they do not have enough energy.	

QUESTION 11		Assessed concept: Connection of Voltmeters	
A voltmeter is connected in series to the circuit below.  What effect will this have on the brightness of the light bulb?		Source	Own experience
		Topic covered according to CAPS document:	“In order to measure voltage, a voltmeter must always be connected across (in parallel) a resistor or battery.” Suggestion made for practical activities. (Department of Basic Education, 2011c, p. 74)
A.	Increase.	Distractor.	
B.	Decrease.	Voltmeters are incorrectly treated as resistors.	
C.	Remain the same.	When voltmeters are connected, they have no effect on the circuit readings even if connected incorrectly.	
D.	The light bulb will no longer shine.	Correct answer.	

ANNEXURE C – TEACHER INTERVIEW QUESTIONS

QUESTION 1 – In this question, we will discuss your general teaching approach for the section of electrical circuits.

1.1 What are the main ideas that you intend the learners to know about in this section? Please sequence them in the order that you taught them.

Click or tap here to enter text.

1.2 Which concepts, within these main ideas, do you find difficult for learners to understand? Can you give reasons why you think learners find it difficult to understand this topic?

Concept	Reason
Click or tap here to enter text.	Click or tap here to enter text.
Click or tap here to enter text.	Click or tap here to enter text.
Click or tap here to enter text.	Click or tap here to enter text.
Click or tap here to enter text.	Click or tap here to enter text.

QUESTION 2 In this study, a representation is referred to as different ways of formulating the subject matter so that learners can understand it. Examples of representations include analogies, diagrams, pictures, equations, simulations, experiments, practical activities etc.

Please identify and explain how you used one or more representation/s to teach concepts in electrical circuits.

Representation	How this representation was used in class	Source of representation	Strengths	Limitations
Click or tap here to enter text.	Click or tap here to enter text.	Click or tap here to enter text.	Click or tap here to enter text.	Click or tap here to enter text.

Click or tap here to enter text.	Click or tap here to enter text.	Click or tap here to enter text.	Click or tap here to enter text.	Click or tap here to enter text.
Click or tap here to enter text.	Click or tap here to enter text.	Click or tap here to enter text.	Click or tap here to enter text.	Click or tap here to enter text.

QUESTION 3 In this question, we will discuss a few of the results of the electrical circuits diagnostic test that your learners completed.

3.1 The results from the learner tests revealed that many learners got question correct indicating that they seem to successfully grasp the concept of .

a. What do you think contributed to the successful understanding of this idea?

Click or tap here to enter text.

3.2 The results from the learner tests revealed that many learners got question incorrect indicating that they hold the misconception of .

b. What do you think could be the cause for learners misunderstanding this idea?

Click or tap here to enter text.

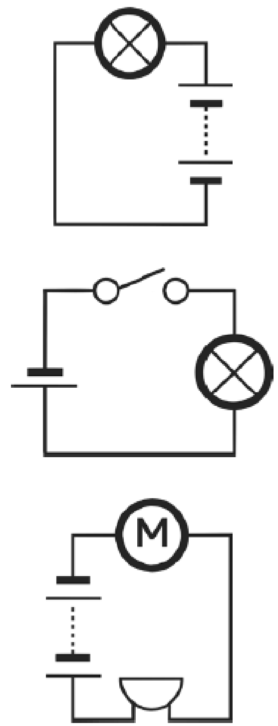
ANNEXURE D – WORKSHEET 1 FROM TEACHER B

Interpreting and Drawing Circuit Diagrams

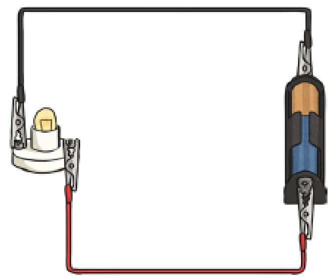
I can recognise and draw scientific circuit symbols.

Use the Scientific Circuit Symbols Mat to help.

Look at the circuits below and label each part.



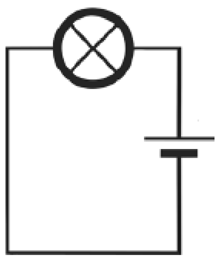
Draw the following circuit using the scientific circuit symbols.

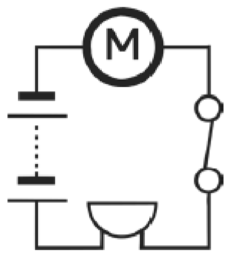


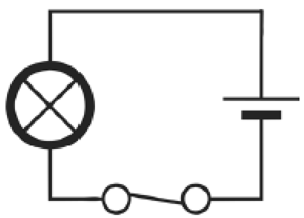
Interpreting and Drawing Circuit Diagrams

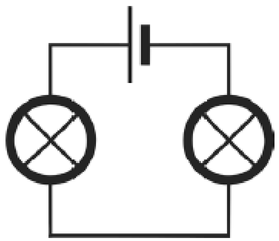
I can recognise and draw scientific circuit symbols.

Look at the circuits below and label each part.

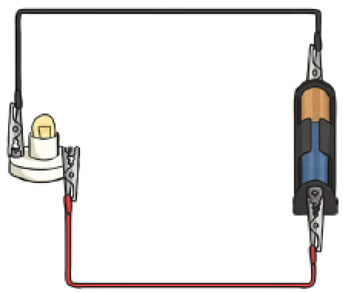


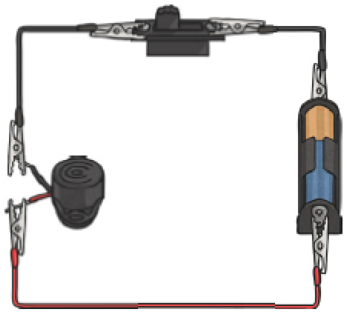






Draw the following circuit using the scientific circuit symbols.





ANNEXURE E – WORKSHEET 2 FROM TEACHER B

Electrical currents

TASK 1: CURRENT IN SERIES AND PARALLEL CIRCUITS

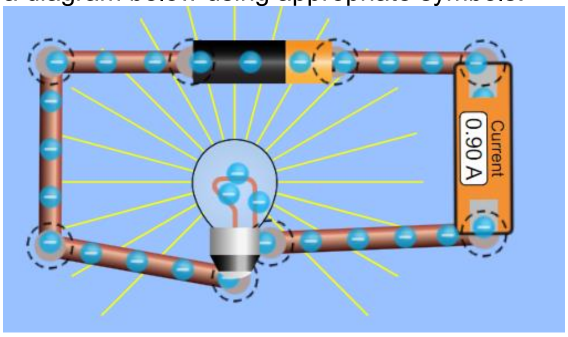
Part 1: Background

1. What is current?
2. What are the units for current?
3. Which instrument is used to measure current? Draw the symbol to represent it on a series circuit

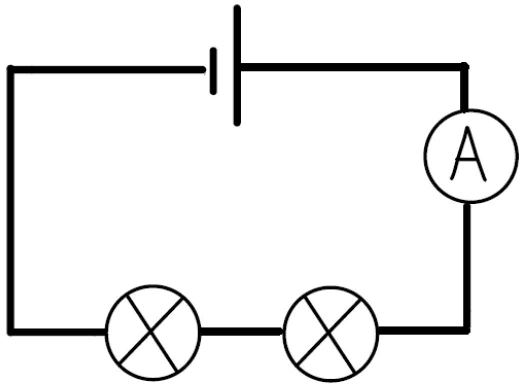
Part II: Investigation

Log onto PhET Circuit construction kit and go to "lab"

1. Construct a simple series circuit with one light bulb on the lab. Draw the constructed circuit as a diagram below using appropriate symbols.



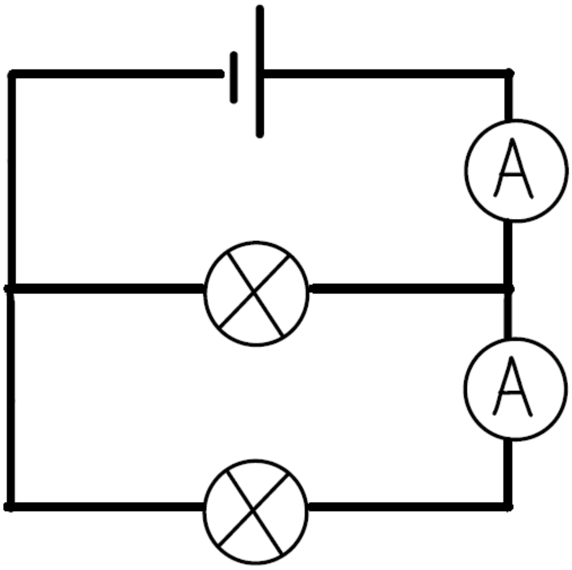
2. Construct the series circuit as shown below. Write observations on the brightness of the lamp and the current. This is called a series circuit.



- *Observations*

………

3. Add a second bulb to the circuit as shown below. This is called a parallel circuit. Write observations on the brightness of the lamps and the current of the circuit.



- *Observations*

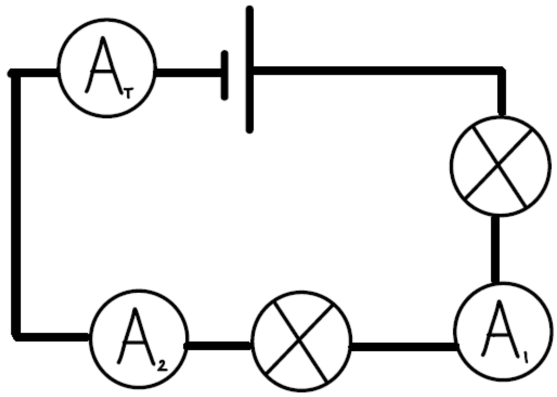
……
……………………………………………………..………

4. Summarise series circuit vs parallel circuit- *complete the close passage below*

In a …………………………… circuit, the components are …………………………… side by side. This gives the current several different …………………………… for it to flow around. If one bulb blows, the other bulbs will …………………………… lit as the circuit is still complete. In a series circuit, the …………………………… are connected end to end in a …………………………… If one bulb breaks, the whole circuit will go …………………………… and none of the bulbs will light as the circuit is …………………………… complete.

out parallel remain loop not paths connected components

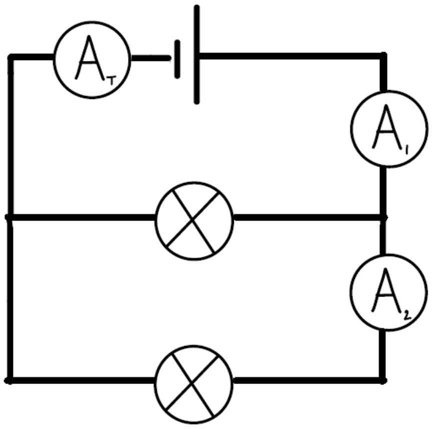
5. Set up the circuit as shown below. Write down the values on the ammeter.



- *Observations about current*

………

Set up the circuit as shown below. Write down the values on the ammeter.



Observations about current

………

Current in a circuit:

Write a conclusion for current in a circuit in a **series** circuit

………

Formula

Write a conclusion for current in a circuit in a **parallel** circuit

………

Formula

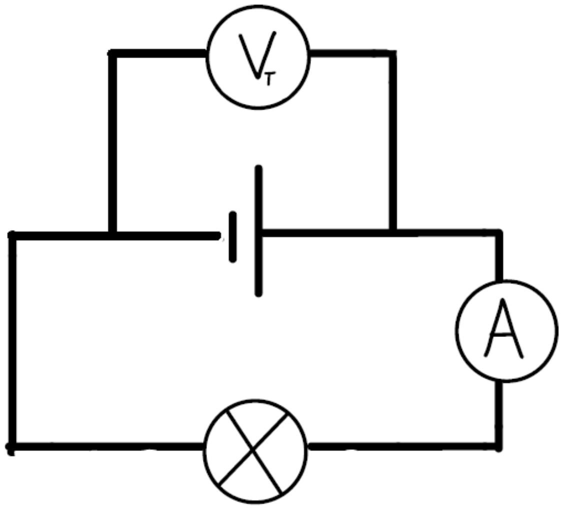
TASK 2: VOLTAGE IN SERIES AND PARALLEL CIRCUITS

Part 1: Background

1. What is voltage?
2. What are the units for voltage?
3. Which instrument is used to measure voltage? Draw the symbol to represent it on a series circuit

Part II: Investigation

1. Set up the diagram below and record each of the voltages. Write down any observations.

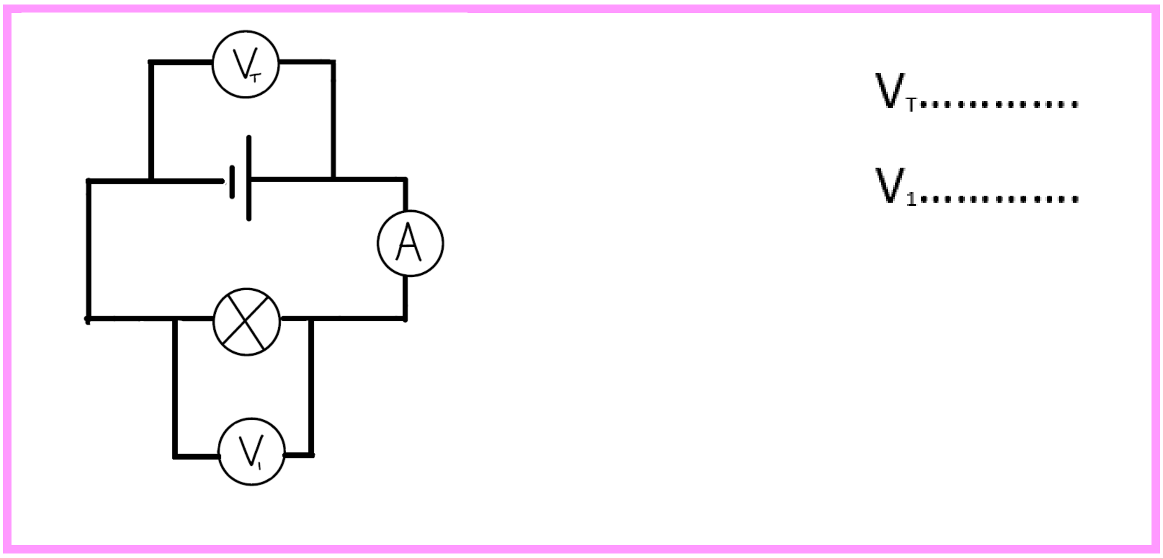


V_T............

- *Observations*

....
....
....

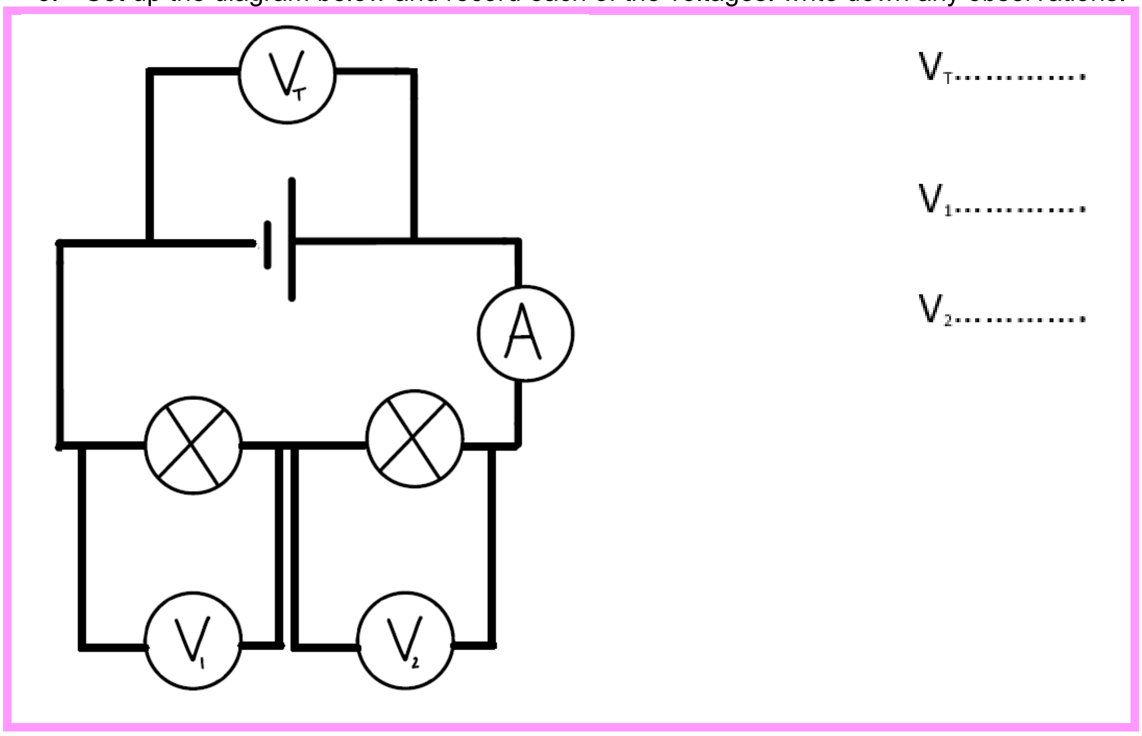
2. Set up the diagram below and record each of the voltages. write down any observations.



Observations

....

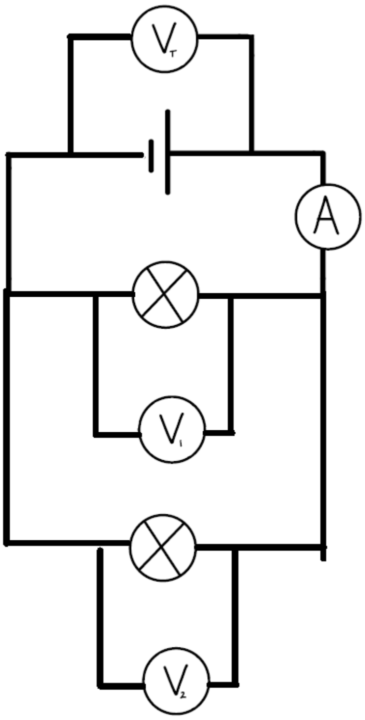
3. Set up the diagram below and record each of the voltages. write down any observations.



Observations

....
....

4. Set up the diagram below and record each of the voltages. write down any observations.



V_T.............

V_1.............

V_2.............

Observations

....

Voltage in a circuit:

Write a conclusion for voltage in a circuit in a **series** circuit

....
....

Formula

Write a conclusion for voltage in a circuit in a **parallel** circuit.

....
....

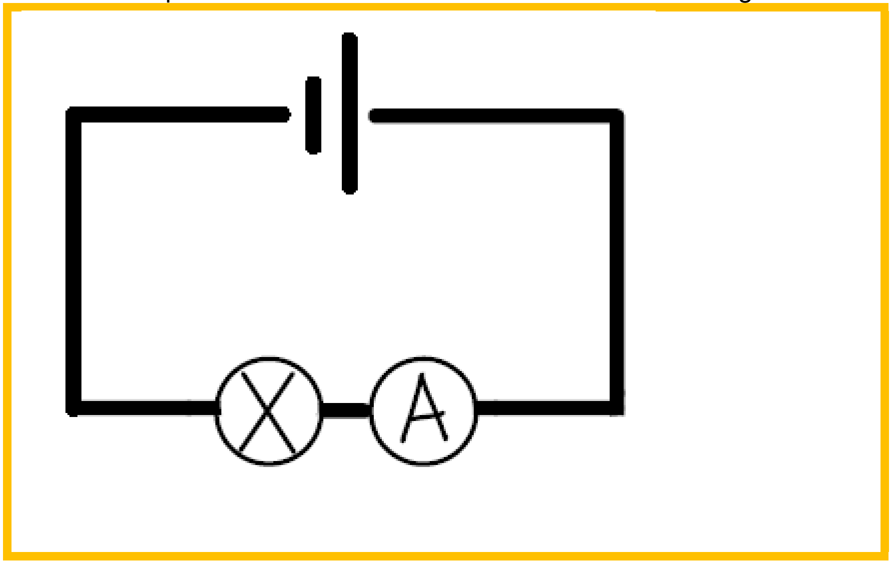
Formula

ANNEXURE F – WORKSHEET 3 FROM TEACHER B

Resistance

TASK 1:

1. Set up the circuit as shown below. Record the following.

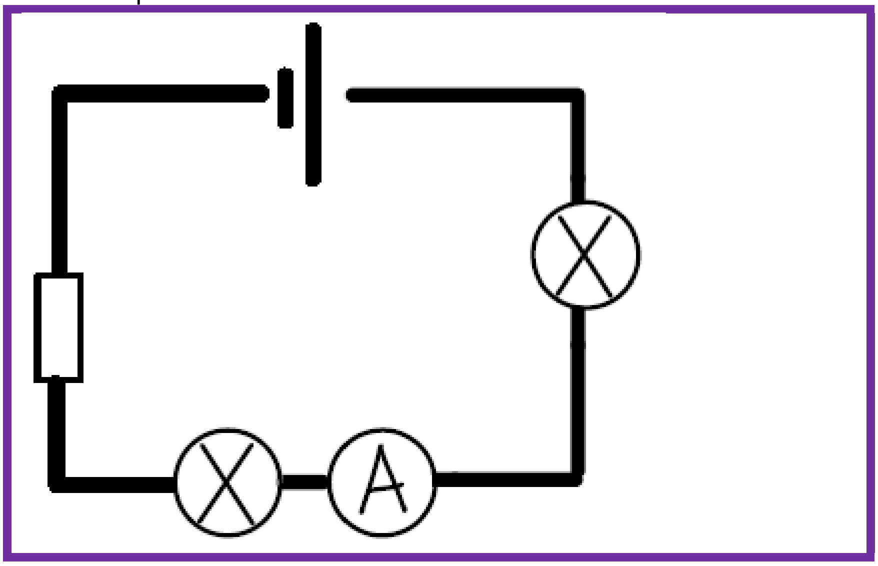


Current: …………………

Voltage of Battery: …………………

Voltage of bulb…………………

2. Add in a second bulb and a resistor. The circuit should be set up as shown below. Record the required data.

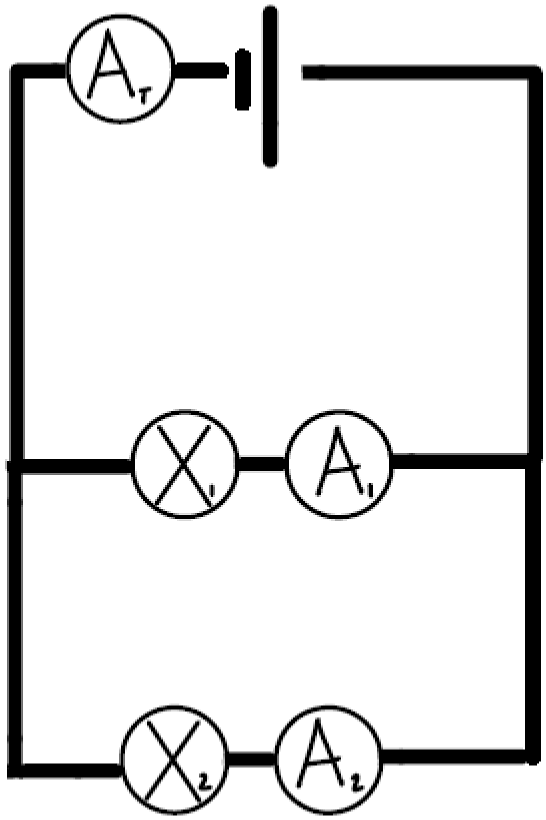


Current: …………………

Voltage of Battery: …………………

Voltage of bulb…………………

3. Set up a parallel circuit as shown below and collect the following sets of data.



Current (A_T): ………………….

Current (A_1): ………………….

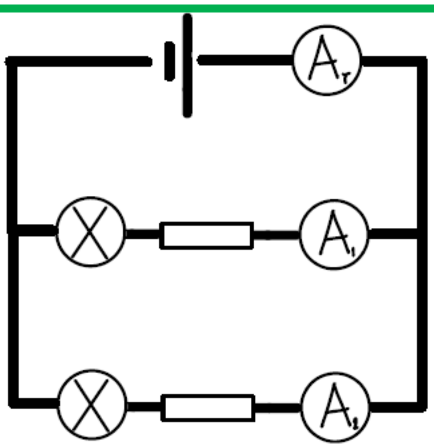
Current (A_2): ………………….

Voltage of Battery: ……………….

Voltage of Bulb 1: ………………….

Voltage of Bulb 1: ………………….

4. Add in 2 resistors and record the data from the circuit below.



Current (A_T): ………………….

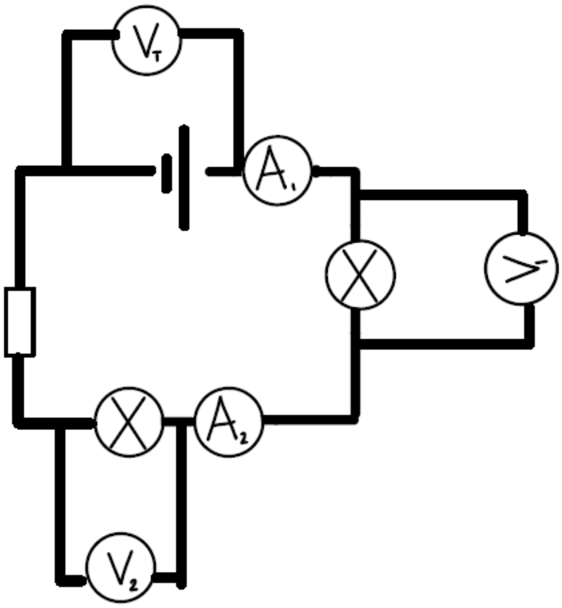
Current (A_1): ………………….

Current (A_2): ………………….

- What is a resistor? …………………………………………………………………………………………………
- What is the effect a resistor has on a circuit? …………………………………………………………………………………………………
- Why would a circuit require a resistor? ……………………………………………………………………………………………

TASK 2:

5. Set up the series circuit below and record the voltage and current.



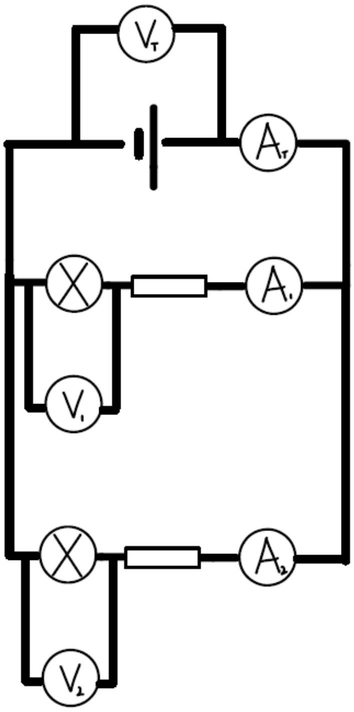
Current (A$_1$): ....

Current (A$_2$): ....

Voltage (V$_1$): ....

Voltage (V$_2$): ....

6. Set up the parallel circuit below and record the voltage and current.



s

Current (A$_T$): ....

Current (A$_1$): ....

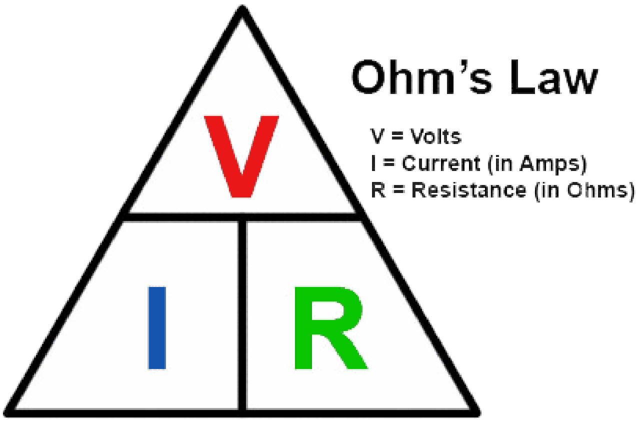
Current (A$_2$): ....

Voltage (V$_T$): ....

Voltage (V$_1$): ....

Voltage (V$_2$): ....

TASK 3: CALCULATING RESISTANCE



$V = I \cdot R$ (volts = amps times ohms)

$I = \frac{V}{R}$ (amps = volts divided by ohms)

$R = \frac{V}{I}$ (ohms = volts divided by amps)

1. What is the voltage if a resistance of 25 Ω produces a current of 250 amperes?
2. What is the current produced by a voltage of 240 V through a resistance of 0.2 Ω
3. What voltage is necessary to produce a current of 200 amperes through a resistance of 100 Ω?
4. What resistance would produce a current of 120 amps from a 6-V battery?
5. What is the current produced by a 9-V battery flowing through a resistance of 200 Ω?
6. What voltage produces a current of 500 amps with a resistance of 50 Ω?
7. What resistance would produce a current of 200 amps with a voltage of 2,000 V?
8. What is the current produced with a 9-V battery through a resistance of 100 Ω?