Investigating the effect of using PhET interactive simulations on Grade 12 learners' performance in electric circuits in the Tubatse Circuit

BY

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DEDICATION

This study is dedicated to the support of my family provided by my parents, as well as my wife Phuti, and our daughters Reitumetse, Relebogile, and Reabetswe, whose care and love have greatly contributed to my academic journey.

DECLARATION

I hereby declare that ‘*investigating the effect of using PhET interactive simulations on Grade 12 learners' performance in electric circuits in the Tubatse circuit’* is an original work completed solely by myself. All resources acknowledged in this study have been duly recognised and cited as references, and this research has not been previously submitted to any other academic institutions.

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Student

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God bless you.

ABSTRACT

Learners often struggle with electric circuits in Physical Sciences due to ineffective teaching approaches and limited access to laboratory equipment and technological tools. This study investigated the effect of using PhET interactive simulations on Grade 12 learners' performance in electric circuits. A total of 102 learners from a rural school in the Sekhukhune East Education District, Limpopo Province, were selected through convenience sampling. A quasi-experimental design with a non-equivalent control group was adopted. Both the experimental (n = 57) and control (n = 45) groups completed a pre-test before the intervention. The experimental group received instruction using PhET simulations, while the control group received traditional instruction without simulations. Post-test scores were then compared using independent t-tests. Results evidencing a significant difference between pre-test and post-test scores in the EG group (t (57) = 0.0000, $p < 0.05$), whereas the control group showed no significant difference (t (45) = 0.285, $p > 0.05$). A higher Pearson correlation coefficient was observed for the experimental group (0.913) compared to the control group (0.382), suggesting a stronger link between simulation-based instruction and learners' ability to address higher-order cognitive questions. These results reflect the potential of PhET simulations to enhance learners' understanding and performance in electric circuits, highlighting their usefulness in contexts where traditional resources may be limited.

Key Concepts: PhET simulations, Grade 12 Physical Sciences, Electric Circuits

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CHAPTER ONE: INTRODUCTION AND BACKGROUND

Background and Motivation of the study

Education is defined as the process by which individuals acquire knowledge, skills, values, and attitudes to reach their full potential and participate actively in society (UNESCO, 2024) Within this broader context, science education plays a crucial role in equipping learners with the ability to explore, understand, and apply scientific concepts in real-world contexts (UNESCO, 2024). The International Council for Science (2011) states that science education promotes critical thinking, problem-solving, and evidence-based reasoning, empowering individuals to make informed choices in a rapidly evolving, technology-driven world. In the African context, science education holds strategic importance for achieving long-term development goals (African Union Commission, 2015). In South Africa, science education has been prioritized to promote equity, redress historical inequalities, and support socio-economic progress (Bertram, 2024). As part of the National Curriculum Statement (NSC), science education provides learners with opportunities to engage in inquiry-based learning, develop scientific language, and apply knowledge to solve contextual problems (Department of Basic Education [DBE], 2011). Physical Sciences is one such science subject in the South African curriculum that reflects both national aspirations and global scientific competencies.

In South Africa, Physical Sciences is one of the core subjects offered at the Further Education and Training (FET) phase, combining physics and chemistry to foster deep conceptual understanding and scientific inquiry. Internationally, Physical Sciences education supports learners in developing skills to interpret data, apply scientific models, and understand phenomena across energy, matter, and motion (OECD, 2024). The South African Curriculum and Assessment Policy Statement (CAPS) defines Physical Sciences as the systematic study of physical and chemical phenomena through observation, experimentation, and theoretical interpretation (DBE, 2011). Furthermore, the CAPS aims to prepare learners for further studies in science, technology, engineering, and mathematics (STEM) fields and to participate meaningfully in a knowledge-based society. The CAPS organizes Physical Sciences into key knowledge strands that include Mechanics, Waves, Electricity and

Magnetism, Matter and Materials, Chemical Change, and Chemical Systems (DBE, 2011). These topics are introduced across Grades 10 to 12 and are designed to build both conceptual progression and application skills. Among these, the topic of electric circuits serves as a foundational component within the Electricity and Magnetism strand.

Electric circuits form one of the key focus areas in the Electricity and Magnetism section of the CAPS Physical Sciences curriculum for Grades 10 to 12. This topic helps learners understand how electrical energy moves through a closed path, how different components in the circuit behave, and how energy is used in devices like bulbs and resistors. In Grade 10, learners are introduced to basic circuit elements such as batteries, switches, bulbs, resistors, and wires. They learn how to draw and interpret simple circuit diagrams using standard symbols, as required by CAPS (DBE, 2011). In Grade 11, learners build on this by exploring the relationships between voltage, current, and resistance. They use Ohm's Law to calculate how these quantities interact in both series and parallel circuits. Learners also begin to understand how energy is conserved and how electric power is calculated and used in everyday life (DBE, 2011). In Grade 12, the curriculum deepens this knowledge by introducing more complex circuit analysis, including internal resistance, the total emf of cells in series, and the effect of resistors in mixed combinations. Practical investigations, such as measuring current and voltage in a circuit using ammeters and voltmeters, are strongly encouraged to help learners apply their theoretical understanding (DBE, 2011). These investigations are guided by the scientific process skills promoted throughout the curriculum, such as hypothesising, observing, recording results, and drawing conclusions (DBE, 2011). According to Ramnarain and Hlatswayo (2018), the CAPS approach to electric circuits supports both content mastery and inquiry-based learning through experiments and data interpretation. By the end of Grade 12, learners should be able to explain how current flows, how potential difference affects components, and how electrical power is used in homes and industries. Although the curriculum sets a clear progression and encourages hands-on learning, many learners face challenges in their learning of electric circuits.

Challenges in the learning of electric circuits are reported in the annual National Diagnostic Reports published by the South African Department of Basic Education. These reports show that many learners struggle to understand and apply basic concepts related to current, resistance, and potential difference. Additionally, national assessments have highlighted a disconnect between the curriculum's emphasis on inquiry and the nature of high-stakes assessments, which often prioritize rote knowledge over higher-order thinking (Edwards, 2010). These challenges limit the transformative potential of Physical Sciences education and call for ongoing curriculum reform, investment in teacher professional development, and the integration of contextually responsive pedagogies. Studies have revealed issues such as underprepared teachers, insufficient laboratory resources, and a gap between curriculum goals and actual classroom practice (Kibirige et al.,2014; Mpungose, 2021; Soyikwa & Boateng, 2024). According to the 2023 Diagnostic Report, common errors include incorrectly calculating total resistance, failing to differentiate between series and parallel circuits, and misunderstanding how current behaves at junctions (DBE, 2023). Learners often memorise formulas without grasping the underlying concepts, which limits their ability to solve unfamiliar problems. Gadzikwa (2018) observed that Grade 10 learners had difficulty connecting theory to real-life applications, particularly when asked to explain how current flows in direct current circuits.

Misconceptions such as “current is used up” or “current divides unequally in all branches” are common and persistent, as found in a study by Manunure et al. (2020) with secondary school learners. Similarly, Bantolo and Mistades (2021) noted that learners had difficulty visualising invisible aspects of circuits, such as the movement of electrons or the concept of resistance, which made it hard for them to reason about changes in a circuit. These issues are often made worse when lessons rely too heavily on textbook explanations or abstract theory, without the aid of hands-on tools or visual models. Banda and Nzabahimana (2021) argue that when learners are not given opportunities to interact meaningfully with circuit concepts, they fail to develop accurate mental models. Hence, Banda and Nzabahimana (2021) encourage the use of interactive tools such as PhET simulations to support deeper conceptual understanding and help address these ongoing challenges.

PhET simulations are interactive, research-based virtual environments developed by the University of Colorado Boulder to facilitate the teaching and learning of physics concepts (Perkins et al., 2006). These simulations allow learners to visualize and manipulate scientific phenomena in ways that traditional teaching methods often cannot achieve (Perkins et al., 2006; Taneo & Moleno, 2021). Covering a wide range of physics topics, including mechanics, electricity, magnetism, and thermodynamics, PhET simulations promote active learning and hands-on exploration, fostering a deeper understanding of the underlying principles of physics (Khaeruddin & Bancong, 2022; Masruroh et al., 2021).

The effectiveness of PhET simulations in enhancing learning outcomes is well-documented. For instance, Khaeruddin and Bancong (2022) found that PhET simulations significantly improved learners' critical thinking skills and fostered positive attitudes toward physics. Similarly, Putranta et al. (2019) reported significant increases in learners' academic achievement in physics when PhET simulations were integrated into their learning experiences. Research also highlights the adaptability of PhET simulations, which effectively replace traditional laboratory experiences, particularly in contexts where access to physical equipment is limited (Masruroh et al., 2021). For example, Ismalia et al. (2022) demonstrated that PhET simulations not only engaged learners but also enhanced their conceptual understanding of static electricity when used as a substitute for practical tools. The interactive nature of PhET simulations aligns with inquiry-based emphasizing active learner participation. By enabling learners to manipulate variables and observe outcomes in real time, these simulations foster critical thinking and deeper cognitive engagement (Dantic & Fluraon, 2022; Uwambajimana, 2023). For example, Banda and Nzabahimana (2021) found that learners who used PhET simulations demonstrated increased motivation and academic achievement, reinforcing the value of simulation-based tools in enhancing conceptual understanding through active knowledge construction.

Despite extensive research demonstrating the effectiveness of PhET simulations in enhancing learning outcomes across various topics and educational levels, there remains a notable gap in studies specifically investigating their impact on Grade 12 learners' performance in electric circuits. This gap is particularly pronounced in the context of the Tubatse Circuit, a region characterized by unique educational challenges. The Tubatse Circuit, like many other rural and semi-rural areas in South Africa, faces significant barriers to effective teaching and learning, including a lack of access to well-equipped laboratories, limited technological infrastructure, and a shortage of qualified Physical Sciences teacherrs. These challenges often hinder the effective teaching of abstract and practical-oriented topics such as electric circuits, which require hands-on experimentation and visualization for deep conceptual understanding (Kibirige et al., 2014; Motlhabane, 2013).

Furthermore, the Tubatse Circuit is part of a broader educational system that consistently reports suboptimal learner performance in Physical Sciences, as reflected in the National Senior Certificate (NSC) examination results. Electric circuits, in particular, are highlighted as a recurring area of difficulty for learners, with poor conceptual understanding and low achievement levels reported in diagnostic reviews by the DBE. These systemic challenges highlight the importance of investigating the use of PhET interactive simulations, which have the potential to bridge gaps in resources and instructional quality, in this rural context. This study, therefore, sought to address this gap by examining how the use of PhET simulations could influence learners' understanding and performance in electric circuits within the Tubatse Circuit. By situating the research within this unique context, the study not only contributes to the global discourse on the use of interactive simulations in Physical Science education but also provides localized insights that are critical for addressing the specific challenges faced by schools in the Tubatse Circuit.

Problem Statement

The problem of this study is that in the Tubatse Circuit many Grade 12 learners encounter persistent difficulties with foundational concepts in electric circuits, despite the structured guidance provided by the CAPS Physical Sciences curriculum. Ideally, learners should be able to understand and apply concepts such as current, voltage, resistance, and power in both series and parallel circuits, using scientific reasoning and experimental data to explain circuit behaviour. They should also be able to construct and interpret circuit diagrams, perform calculations using Ohm's Law, and conduct investigations that develop both conceptual and practical competence (DBE, 2011). However, National Diagnostic Reports have consistently highlighted learners' difficulties in interpreting circuit diagrams, applying Ohm's Law, and distinguishing between series and parallel circuits (DBE, 2023). These persistent learning difficulties are further compounded by learners' limited ability to visualise abstract and invisible aspects of electric circuits, such as electron flow and resistance, which makes it challenging for them to reason accurately about circuit behaviour and predict changes across components (Bantolo & Mistades, 2021). These challenges are often attributed to traditional teaching methods that emphasize theoretical instruction over interactive, visual learning experiences (Gadzikwa, 2018). Consequently, learners develop misconceptions, such as believing that current is consumed within components, which hinder their ability to accurately analyze and construct electrical circuits (Manunure et al., 2020). To address these issues, this study investigated the effect of integrating PhET interactive simulations into the teaching of electric circuits.

The Purpose of the Study, Research Objectives and Hypotheses

1.3.1 Purpose of the Study

The purpose of this study was to investigate the effect of using PhET interactive simulations on Grade 12 learners’ performance in electric circuits within the Tubatse Circuit.

1.3.2 Research Objectives

To fulfil the purpose stated above, the following objectives were formulated:

1. To investigate whether there is a significant difference in learners’ performance in the experimental group (EG) when PhET simulations are used.
2. To investigate whether there is a significant difference in learners’ performance in the control group (CG) when PhET simulations are not used.
3. To examine whether there is a strong relationship between the use of PhET simulations and learners’ ability to respond to higher-order cognitive questions in the EG.
4. To examine whether there is a strong relationship between the absence of PhET simulations and learners’ ability to respond to higher-order cognitive questions in the CG.

1.3.3 Research Hypotheses

To address the aforementioned objectives, the following null (H0) and alternative (HA) hypotheses were tested at the 0.05 significance level:

1. **$H0_1$**: There is no significant difference in learners' performance when PhET simulations are used in the EG.

   HA_1: There is a significant difference in learners' performance when PhET simulations are used in the EG.

2. **$H0_2$**: There is no significant difference in learners' performance when PhET simulations are not used in the CG.

   HA_2: There is a significant difference in learners' performance when PhET simulations are not used in the CG.

3. **$H0_3$**: There is no strong relationship between the use of PhET simulations and the ability of learners in the EG to respond to higher-level cognitive questions.

   HA_3: There is a strong relationship between the use of PhET simulations and the ability of learners in the EG to respond to higher-level cognitive questions.

4. **$H0_4$**: There is no strong relationship between the absence of PhET simulations and the ability of learners in the CG to respond to higher-level cognitive questions.

   HA_4: There is a strong relationship between the absence of PhET simulations and the ability of learners in the CG to respond to higher-level cognitive questions.

CHAPTER TWO: THEORETICAL UNDERPINNINGS

2.1 Introduction

This chapter presents the theoretical foundations that guide the study, focusing on three interrelated frameworks: Sweller's Cognitive Load Theory (CLT) (1990), Mayer's Cognitive Theory of Multimedia Learning (CTML) (1997), and Constructivist Learning Theory (Piaget, 1972; Vygotsky, 1978). These theories offer complementary perspectives on how learners process information, engage with instructional materials, and construct new knowledge. CLT emphasizes the importance of managing cognitive demands during learning, while CTML focuses on optimizing multimedia design to enhance comprehension and retention. Constructivist learning theory underlines the active role of learners in building their own understanding through inquiry and reflection. In the context of this study, which investigates the use of PhET Interactive Simulations to improve Grade 12 learners' understanding of electric circuits, these theoretical frameworks collectively provide a comprehensive foundation for both the design of instructional interventions and the interpretation of learning outcomes.

2.2 Rationale for Using Three Theoretical Frameworks

As already stated in the introductory section of this chapter above, this study draws upon three complementary theoretical frameworks: CLT, CTML, and Constructivist Learning Theory. The integration of these frameworks ensures a comprehensive approach to understanding both the design and pedagogical effectiveness of using PhET interactive simulations to enhance learners' understanding of electric circuits.

CLT provided guidance on managing the mental demands placed on learners during the learning process, emphasizing the need to reduce extraneous load and support schema construction (Sweller et al., 2019). CTML offers specific principles for how visual and auditory information should be presented to optimize cognitive processing and retention (Mayer, 2001). Constructivist Learning Theory complements these cognitive perspectives by focusing on the active role of learners in constructing their own knowledge through exploration, experimentation, and reflection (Piaget, 1972; Vygotsky, 1978; Fosnot, 2013).

Although CLT and CTML primarily address how cognitive processes can be optimized through instructional design, Constructivist Learning Theory emphasizes how learners engage meaningfully with content. In this study, managing cognitive demands alone is insufficient; creating opportunities for active knowledge construction is equally vital. Therefore, the combination of these three frameworks ensures that the instructional intervention is not only cognitively efficient but also promotes deep, inquiry-based learning that is consistent with best practices in science education.

2.3 Cognitive Load Theory

CLT, which proposes that human cognitive capacity is limited, and that effective learning occurs when instructional materials minimize irrelevant demands while maximizing mental effort directed toward understanding (Sweller et al., 2019; Merriënboer & Sweller, 2010). CLT classifies cognitive load into three main categories:

1. **Intrinsic Load**: Related to the complexity of the material and the learner's prior knowledge, which together determine the level of difficulty in processing new information (Sweller et al., 2019; Merriënboer & Sweller, 2010).
2. **Extraneous Load**: Caused by elements in the instructional design that do not directly contribute to learning, such as overly complex or poorly organized materials (Sweller et al., 2019; Merriënboer & Sweller, 2010).
3. **Germane Load**: Refers to the mental resources dedicated to processing and internalizing new information, which is essential for deeper understanding and schema construction (Vandewaetere & Clarebout, 2013; Merriënboer & Sweller, 2010).

By effectively managing these types of load, teachers can help learners develop robust cognitive schemas, leading to improved problem-solving skills and better retention of new knowledge (Merriënboer & Sweller, 2010; Paas et al., 2010). In this study, CLT principles inform the design and implementation of multimedia learning materials for electric circuits, with particular attention given to optimizing cognitive load (Merriënboer & Sweller, 2010; Sweller et al., 2019). This involves ensuring that content complexity aligns with learners' existing knowledge, minimizing extraneous elements that might distract from essential concepts, and enhancing germane load to foster deeper engagement with the material (Merriënboer & Sweller, 2010; Sweller et al., 2019).

The use of CLT in instructional design is especially relevant in complex scientific subjects, such as electric circuits, where learners can easily become overwhelmed by multiple concepts and intricate diagrams (Merriënboer & Sweller, 2010; Sweller et al., 2019). By structuring the PhET simulations and related learning tasks in a way that carefully manages learners’ cognitive load, the study seeks to facilitate higher levels of comprehension and retention. This approach aligns with existing research emphasizing the need to reduce unnecessary cognitive demands while promoting active cognitive processing and the construction of meaningful understanding (Vandewaetere & Clarebout, 2013; Merriënboer & Sweller, 2010; Sweller et al., 2019). In doing so, the study aims to demonstrate how effectively designed instructional materials, grounded in CLT, can enhance both the educational experience and academic outcomes for Grade 12 learners studying electric circuits.

2.4 Cognitive Theory of Multimedia Learning (CTML)

While CLT focuses on optimizing the mental effort required for learning, Mayer’s CTML adds another layer by emphasizing how learners process information through separate visual and auditory channels (Harskamp et al., 2007; Ginns, 2005). According to CTML, effective instructional design uses multiple sensory modalities to reduce overload on any single cognitive channel, thereby enhancing comprehension and retention.

1. **Coherence Principle**: This principle advises removing extraneous details that do not directly support the learning goals, thereby preventing unnecessary cognitive load (Harskamp et al., 2007; Ginns, 2005). By focusing only on essential information, learners can dedicate more cognitive resources to understanding core concepts.
2. **Redundancy Principle**: This principle highlights the importance of avoiding the duplication of information in both written and spoken form (Harskamp et al., 2007; Ginns, 2005). When learners receive the same content simultaneously in text and speech, they may expend extra mental effort reconciling these two sources, which can hinder comprehension.

3. **Modality Principle**: The modality principle advocates presenting content through both visual and auditory channels to make the most of the brain's dual-processing capabilities (Harskamp et al., 2007; Ginns, 2005; Ayres & Paas, 2007). For example, combining narrated explanations with relevant diagrams can help learners form clearer mental models of complex information.

In this study, these CTML principles were integral to the development of PhET simulations and related materials for electric circuits. By leveraging multiple senses, visual diagrams paired with concise narration, learners could explore circuit concepts without experiencing cognitive overload (Harskamp et al., 2007; Ayres & Paas, 2007). This approach streamlines the learning process, ensuring that mental resources are directed toward essential content rather than being consumed by irrelevant details (Ginns, 2005; Ayres & Paas, 2007).

Moreover, incorporating Mayer's principles into the instructional design aligns with research showing that well-structured multimedia environments can significantly improve learners' engagement and comprehension (Harskamp et al., 2007; Ginns, 2005; Ayres & Paas, 2007). By reducing unnecessary cognitive demands and presenting information through multiple channels, the multimedia materials in this study were specifically tailored to enhance understanding of electric circuits (Harskamp et al., 2007; Ayres & Paas, 2007). Such an intentional design not only fosters a more interactive learning experience but also supports deeper cognitive processing, ultimately leading to better academic outcomes.

2.5 Constructivist Learning Theory

Constructivist learning theory asserts that learners actively construct their own understanding and knowledge of the world through experience and reflection (Piaget, 1972; Vygotsky, 1978). Unlike traditional views of learning as the passive absorption of information, constructivism emphasizes that learning occurs when individuals engage meaningfully with content, question assumptions, and collaboratively build new knowledge structures (Priyamvada, 2018). This active, inquiry-driven process is at the heart of effective learning in science education, where abstract concepts often require hands-on exploration to become meaningful.

Two foundational perspectives within constructivism are Jean Piaget's theory of cognitive development and Lev Vygotsky's sociocultural theory. Piaget (1972) proposed that learners build mental models through active exploration, experiencing processes of assimilation and accommodation as they encounter new information. According to Piaget, true understanding arises when learners reorganize their cognitive structures to resolve contradictions between their existing knowledge and new experiences. Vygotsky (1978), on the other hand, highlighted the social nature of learning, emphasizing the role of interaction, language, and cultural tools. His concept of the Zone of Proximal Development (ZPD) suggests that learners achieve higher levels of understanding when supported by more knowledgeable peers or instructors.

In the context of multimedia learning and digital technologies, constructivist principles remain highly relevant. Fosnot (2013) emphasizes that effective constructivist teaching involves creating environments where learners engage in problem-solving, inquiry, and collaboration. Technology-enhanced learning tools, such as PhET Interactive Simulations, precisely provide such environments by allowing learners to experiment with variables, visualize abstract phenomena, and receive immediate feedback on their actions. Learners can build and refine their conceptual understanding of scientific principles through active manipulation and inquiry.

PhET simulations are specifically designed to support constructivist learning. Perkins et al. (2006) argue that simulations create opportunities for exploration, hypothesis testing, and iterative refinement of understanding – processes fundamental to constructivist pedagogy. Rutten et al. (2012) further confirm that simulations encourage inquiry-based learning by enabling learners to generate, test, and revise their own mental models based on observed outcomes.

In this study, the use of PhET simulations to teach electric circuits to Grade 12 learners is grounded in constructivist learning theory. The simulations provide a space where learners are not merely passive recipients of information but are active agents constructing knowledge through interaction and experimentation. Learners manipulate components in virtual circuits, observe cause-and-effect relationships, and adjust their thinking based on feedback, aligning with both Piagetian and Vygotskian notions of active, scaffolded learning.

While Cognitive Load Theory and Cognitive Theory of Multimedia Learning guide the cognitive structuring and multimedia design of instructional materials, constructivist learning theory provides the pedagogical foundation for why simulations were selected as the intervention tool. The combination of these frameworks ensures that learning is not only cognitively efficient but also meaningfully constructed through engagement, inquiry, and reflection.

Thus, constructivist learning theory complements the study’s cognitive theories by ensuring that the pedagogical strategies adopted , namely the integration of PhET simulations , support learners' active role in knowledge construction, particularly within the complex and abstract topic of electric circuits in Physical Sciences.

2.6 How the Three Theories Complement One Another

Although CLT, CTML, and Constructivist Learning Theory approach learning from different perspectives, they complement each other in important ways. CLT focuses on managing learners' cognitive resources by minimizing extraneous demands and optimizing instructional design to enhance schema development (Sweller et al., 2019). CTML builds upon this by providing specific strategies for combining verbal and visual information to promote deeper cognitive processing and retention (Mayer, 2001). Constructivist Learning Theory adds a pedagogical dimension, emphasizing the learner’s active role in constructing understanding through inquiry, exploration, and reflection (Piaget, 1972; Vygotsky, 1978; Fosnot, 2013).

Together, these theories offer a foundation for designing and evaluating effective educational interventions. CLT ensures that cognitive overload is minimized, CTML ensures that multimedia elements are structured to support learning efficiently, and Constructivist Learning Theory ensures that learners are meaningfully engaged in constructing their own scientific knowledge. This integrated theoretical approach is particularly well-suited for the use of PhET Interactive Simulations, which require careful cognitive scaffolding while promoting active, inquiry-based learning. Thus, the study ensures that learners can effectively process complex information about electric circuits, build conceptual models, and apply their understanding to problem-solving tasks by aligning the cognitive structure, multimedia design, and pedagogical engagement strategies.

2.7 Conclusion

This chapter outlined the theoretical underpinnings that inform the study. CLT provided principles for managing learners' cognitive resources by minimizing unnecessary demands and promoting meaningful engagement. CTML offered insights into how visual and auditory elements can be structured to enhance information processing and retention. Constructivist Learning Theory contributed the pedagogical foundation, emphasizing the importance of active, inquiry-based learning where learners construct their own understanding. Together, these frameworks support the design and use of PhET Interactive Simulations in Physical Sciences education, ensuring that the instructional approach is cognitively efficient, pedagogically sound, and aligned with principles of active knowledge construction. The next chapter, the Literature Review, examines previous studies on simulations and multimedia learning tools to situate this study within the broader field of science education research.

CHAPTER THREE: LITERATURE REVIEW

3.1 Introduction

This chapter presents a review of the literature related to the use of simulations in science education, with a particular focus on PhET interactive simulations and their role in teaching electric circuits. The review begins by discussing different types of simulations and their pedagogical advantages, followed by an exploration of the global and local trends in their use. It also examines the specific features and educational value of PhET simulations, supported by empirical studies from both physics and chemistry education. Key insights into learner performance in electric circuits are discussed, especially common misconceptions and cognitive challenges, as well as the systemic issues in teaching this topic in under-resourced contexts like the Tubatse Circuit. This review integrates international and South African literature, including national diagnostic reports and official curriculum documents, to establish a strong foundation for the study. The chapter aims to highlight gaps in research and practice, particularly in how digital tools like PhET are used in rural South African classrooms to support deep conceptual understanding of electric circuits.

3.2 Use of Simulations in Science Education

3.2.1 Definition and Types of Simulations

Simulations in science education refer to computer-generated environments or models that allow learners to explore scientific concepts and phenomena in an interactive, visual, and often hands-on manner without the risks or limitations of a physical laboratory. According to Singh-Pillay (2024), simulation-based learning environments are designed to mimic real-world scientific processes, allowing learners to manipulate variables, observe outcomes, and engage in inquiry-driven tasks. These environments bridge the gap between theoretical knowledge and practical experience by offering learners controlled, repeatable, and visual contexts for experimentation. There are various types of simulations used in science classrooms, each offering different pedagogical affordances.

One common type is the virtual laboratory, which replicates the structure and procedures of real laboratories. These labs enable learners to conduct experiments using digital tools and instruments, often including features such as data logging and feedback on experimental design. Singh-Pillay (2024) found that South African science teachers view virtual labs as valuable alternatives in under-resourced schools, especially where physical equipment is limited or unavailable. Another prominent form is interactive animations, which use simplified visual representations to depict dynamic scientific processes. These are particularly useful for visualizing abstract or invisible concepts such as electric current, magnetic fields, or chemical bonding. As reported by Ouahi et al. (2022), science teachers across various educational settings appreciate animations for their role in enhancing learner comprehension through visualization, especially for topics typically considered difficult or inaccessible through textbooks alone.

Game-based learning simulations constitute a third category. These simulations incorporate elements of gaming, such as rewards, levels, and challenges, to promote motivation and engagement. While game-based simulations are less common in formal classroom settings compared to virtual labs and animations, they have shown promise in fostering sustained learner interaction and improving problem-solving skills in experimental contexts (Ndihokubwayo et al., 2020).

Additionally, scenario-based simulations, which immerse learners in real-life problem-solving situations (e.g., designing an electric circuit for a real-world application), are gaining traction. These simulations are valued for fostering critical thinking and decision-making under simulated constraints, preparing learners for authentic scientific inquiry (Singh-Pillay, 2024). Across these types, simulations offer differentiated levels of interaction. While some are exploratory, allowing free manipulation of variables, others are guided, providing structured steps for learners to follow. Banda and Nzabahimana (2023) emphasize that regardless of format, simulations promote active cognitive engagement and support the development of conceptual understanding when well-integrated into lesson planning.

Simulations in science education encompass a spectrum of tools – including virtual labs, animations, and game-based models – that transform abstract scientific content into interactive and accessible learning experiences. These tools align well with inquiry-based pedagogy and offer potential for improving learner engagement and understanding.

3.2.2 Advantages of Using Simulations in Science Education

Simulations offer a range of advantages in science education. They enhance learners' ability to visualize abstract concepts, promote active engagement, and provide cost-effective solutions to practical science learning, especially in under-resourced schools. These tools support inquiry-based learning by creating virtual spaces where learners can manipulate variables, observe outcomes, and receive immediate feedback.

One of the most widely recognized benefits of simulations is their ability to help learners visualize invisible and abstract processes. Scientific phenomena such as current flow, resistance, and subatomic interactions are difficult to explain using static diagrams or verbal explanations alone. Simulations make these processes visible and dynamic, allowing learners to observe cause-and-effect relationships in real time. For example, Singh-Pillay (2024) notes that science teachers in South Africa found simulations particularly helpful in improving learner understanding of the invisible aspects of electricity and magnetism. Likewise, Ouahi et al. (2022) report that learners found simulations effective in visualizing complex scientific systems.

In addition to improving conceptual clarity, simulations also increase learner engagement and motivation. Learners can interact with the content by testing hypotheses, adjusting conditions, and predicting outcomes. This hands-on approach leads to deeper understanding and sustained interest. Banda and Nzabahimana (2023) found that Malawian learners exposed to PhET simulations demonstrated not only improved performance but also increased enthusiasm for physics. Similarly, Ndihokubwayo et al. (2020) observed that simulations helped learners in Rwandan classrooms develop confidence and curiosity through experimentation.

Another advantage is the cost-effectiveness of simulations, particularly in contexts where laboratory equipment is scarce or outdated. Many schools in rural and township areas cannot afford or maintain fully equipped science labs. Simulations, such as those offered by PhET, allow teachers and learners to conduct virtual experiments without needing physical materials. According to Singh-Pillay (2024), this flexibility enables teachers to deliver practical science education even when resources are limited, levelling the educational playing field for disadvantaged learners.

Simulations also support safe and repeatable learning. Learners can explore concepts without the risks associated with physical labs, such as breakages or harmful chemical reactions. In addition, simulations can be revisited multiple times, giving learners the opportunity to consolidate their understanding at their own pace (Ouahi et al., 2022; Adiguzel et al., 2020).

Finally, simulations accommodate different learning styles by combining visual, symbolic, and textual information. This multimodal delivery allows learners to understand concepts from multiple angles, which improves retention and helps bridge learning gaps (Ouahi et al., 2022). Learners also enjoy the visually rich and interactive nature of simulations, which can foster more positive attitudes toward science learning (Banda & Nzabahimana, 2023; Ouahi et al., 2022).

Overall, the advantages of simulations in science education are well-documented across global and African contexts. They improve visualization, enhance learner motivation, offer practical alternatives to physical labs, and provide a safe, flexible environment for repeated experimentation. These benefits are especially important in under-resourced educational settings, where access to physical materials is limited and large class sizes reduce opportunities for hands-on learning.

3.2.3 Challenges in Implementing Simulations in Science Education

Simulations offer many benefits for teaching science, but their effective use faces several challenges – especially in under-resourced contexts. These include technological access, teacher preparedness, curriculum limitations, and lack of systemic support. One of the main obstacles is limited access to digital infrastructure. In many schools, especially in rural areas, teachers and learners do not have reliable access to computers, projectors, or internet connectivity. In a South African study, Singh-Pillay (2024) highlighted that schools often lacked the basic technological setup to run simulations, leading to reliance on outdated, teacher-centred methods. Similar findings are reported across Africa and the Middle East, where many teachers expressed frustration with the inconsistent availability of digital resources (Ouahi et al., 2022; Banda & Nzabahimana, 2023; Mahdi & Laafou, 2022). Even when hardware is present, it is not always maintained, updated, or available to all learners, further deepening the digital divide (AlGerafi et al., 2023).

The digital divide not only limits access to equipment but also affects learners' ability to learn independently using simulations. While urban schools may integrate PhET and similar tools into regular instruction, learners in under-resourced settings often encounter simulations for the first time during intervention studies. This creates a knowledge gap that affects how easily they can benefit from these tools (Falloon, 2020).

Another key challenge is teacher training and confidence. Many teachers lack the necessary skills to integrate simulations into their classroom instruction effectively. According to Mafor and Ramnarain (2021), even when simulations are made available, teachers feel unprepared to use them without further support. In Morocco, Mahdi and Laafou (2022) found that teachers preferred traditional chalk-and-talk methods because they had limited training on how to use educational technologies. Similarly, Singh-Pillay (2024) found that although South African teachers saw the potential of simulations, they lacked digital pedagogical skills and confidence to incorporate them meaningfully into lessons.

The curriculum structure also limits the adoption of simulations. CAPS (Curriculum and Assessment Policy Statement) in South Africa prioritizes syllabus coverage and final examinations, placing pressure on teachers to focus on content delivery rather than exploration or learner-centred activities. In such time-constrained environments, simulations are sometimes viewed as a luxury rather than a necessity (Singh-Pillay, 2024; Rakolobe & Teise, 2024). Overcrowded classrooms further complicate this, making it difficult for teachers to monitor simulation activities effectively or provide learners with hands-on interaction.

Moreover, simulation content does not always align with curriculum requirements, particularly in countries where the simulation interfaces are in English, but learners speak local languages. Mafor and Ramnarain (2021) observed that language barriers made it hard for learners to follow instructions and understand simulation feedback, reducing learning gains.

There is also a lack of policy-level support and strategic integration. While some education systems promote the use of digital tools broadly, specific policies supporting simulation-based learning in science education are limited or missing. As Tabatabai

(2020) points out in the medical education context, simulation adoption surged during the COVID-19 pandemic due to necessity, but long-term integration requires infrastructure, training, and curriculum alignment. In school settings, without institutional commitment and regular teacher support, simulation usage remains sporadic and unsustainable (Lin et al., 2021; Rakolobe & Teise, 2024).

Finally, technical challenges such as slow internet, lack of IT support staff, and unstable electricity supply in many schools continue to undermine simulation integration, especially in rural areas (Falloon, 2020; Hrynevych et al., 2021).

3.2.4 Global Trends in Simulations Use

The use of simulations in science education has grown across different parts of the world, with many countries adopting them to support teaching, improve understanding, and overcome practical challenges. This growth reflects a global shift in how science is taught, especially in classrooms where resources are limited or where concepts are too difficult to show through physical experiments.

In South Africa, Singh-Pillay (2024) reports that teachers in under-resourced schools found simulation-based learning helpful. They used it to overcome the lack of laboratory equipment and to help learners understand complex ideas, especially in Physical Sciences. In the same context, simulations like PhET helped teachers move away from only using chalk-and-talk methods and instead involve learners in active learning. Similarly, Rakolobe and Teise (2024) explain that despite policy support for technology in education, many schools in the region still rely on traditional teaching due to limited support and uneven access to technology.

In Morocco, Mahdi and Laafou (2022) found that secondary school teachers viewed simulations positively. They used PhET and similar tools to support science lessons, especially for explaining abstract topics like electric circuits and atomic structures. However, teachers needed more training and infrastructure to use the tools effectively. Ouahi et al. (2022) also noted that Moroccan science teachers believe simulations help learners visualize content better than textbooks.

Ndihokubwayo et al. (2020) used PhET and YouTube videos to help learners understand optics. The study showed that these tools made learning easier and increased learner interest in science. Teachers used simulations during regular lessons, which made abstract ideas more concrete and improved classroom participation.

Banda and Nzabahimana (2023) found that using simulations in physics classes improved learner motivation and understanding. The learners performed better on electricity topics compared to those who were taught without simulations. The study showed that simulations gave learners a chance to experiment and understand at their own pace.

Research shows that simulations support flexible learning. According to a study Ndihokubwayo et al. (2020), simulations helped teachers deliver science content to learners in both urban and rural settings. Learners who used simulations became more confident in applying science concepts, especially when simulations were used together with regular lessons.

Utama et al. (2024) showed that simulations improved learners' understanding of the solar system. The simulations helped explain movement and positions of planets, which are difficult to show with real objects. Learners in the study said they enjoyed using simulations and found it easier to remember what they had learned.

Teachers have used simulations widely to improve learners’ understanding in subjects like chemistry and physics. For example, Banda & Nzabahimana (2023) discusses how virtual chemistry labs supported learner research and made it easier to practice scientific methods in a safe, repeatable way.

Ouahi et al. (2022) reports that simulations such as PhET are commonly used in physics education. These tools help learners test ideas by changing variables and seeing what happens. Teachers report that simulations encourage learners to ask questions and try new ways to solve problems. Wang et al. (2024) supports this by explaining that simulations in American classrooms allow learners to control experiments without the cost and risk of real equipment.

Globally, simulation use continues to increase as more schools and governments recognize its value. However, the level of use still depends on the availability of digital tools, teacher training, and how well simulations fit into the school curriculum. In many parts of the world, such as South Africa, Morocco, and Malawi, simulations are used more as a support tool rather than being fully included in everyday lessons. Hrynevych et al. (2021) emphasize that using digital tools like simulations must be part of a bigger education strategy, especially in STEM fields.

Overall, countries around the world have used simulations to make science more interactive and understandable. Studies in Africa, Asia, Europe, and the USA show that simulations improve learning, increase interest in science, and help teachers explain difficult topics. Despite this progress, many rural and under-resourced schools still struggle to use simulations regularly due to lack of training, poor infrastructure, and pressure to cover the curriculum quickly.

In South Africa, especially in rural places like the Tubatse Circuit, there is little research on how simulations like PhET are used in actual classroom teaching. There is also limited evidence on how simulations affect learner performance in Physical Sciences at the Grade 12 level. This study helps to fill that gap by investigating how PhET simulations impact learning about electric circuits in under-resourced South African classrooms.

3.3 PhET Simulations: Benefits and Limitations

3.3.1 What are PhET Simulations

As introduced in Chapter 1 under the *Background and Motivation* section, PhET (Physics Education Technology) simulations are interactive, computer-based learning tools developed to enhance the teaching and learning of science and mathematics concepts. These simulations originated in 2002 at the University of Colorado Boulder under the leadership of Carl Wieman, a Nobel Prize-winning physicist, with the goal of supporting conceptual understanding through inquiry-based, visual, and interactive learning experiences (Perkins et al., 2006). PhET simulations are research-informed digital resources designed to help learners grasp abstract scientific concepts by providing opportunities to manipulate variables, visualize outcomes, and engage in exploratory learning. While the *Background and Motivation* section introduced their educational value, this section delves deeper into their theoretical and functional basis, subject coverage, and interactive features.

PhET simulations are grounded in physics education research, cognitive science, and multimedia learning theory. These tools support constructivist learning by engaging learners actively in the knowledge-construction process. Learners are not merely passive recipients but interact with digital representations of scientific systems to test ideas and receive immediate feedback (Saudelli et al., 2021; Cetinkaya & Kirilmazkaya, 2022). For example, the “Circuit Construction Kit” allows users to build electrical circuits virtually, manipulate components like resistors and batteries, and observe changes in current and voltage dynamically (Taibu et al., 2021; Banda & Nzabahimana, 2021).

The simulations cover a wide range of subjects, including physics, chemistry, biology, earth science, and mathematics. They are freely accessible and available in over 90 languages, making them globally adaptable and inclusive (Özcan et al., 2020; Rahmawati et al., 2022). This accessibility is especially valuable in under-resourced settings where laboratory equipment may be limited or absent. Learners can conduct virtual experiments on topics such as Ohm’s Law, Newton’s Laws, wave interference, or atomic interactions, thereby fostering experiential learning without the risks or costs of physical labs (Prima et al., 2018).

Olugbade et al. (2024) note that the visual and interactive design of PhET simulations enhances learners’ attention and supports the development of scientific reasoning. By encouraging learners to test predictions, explore scenarios, and receive immediate visual feedback, these simulations help bridge the gap between theoretical knowledge and practical application. This design also supports learners who struggle with abstract content by providing intuitive, manipulable representations that make invisible processes, like current flow or voltage changes, visible (Pranata, 2024).

Moreover, PhET simulations are built with multiple representations in mind: visual animations are often accompanied by numerical data and symbolic models, which help learners connect different forms of information (Cetinkaya & Kirilmazkaya, 2022; Perkins et al., 2006). This multimodal approach strengthens conceptual understanding and supports diverse learning styles.

In summary, while Chapter 1 introduced PhET simulations as interactive tools that align with modern pedagogical goals in science education, this section has expanded the explanation by showing that PhET simulations are grounded in solid theoretical frameworks, designed with learner interactivity at their core, and accessible across a broad range of science and mathematics subjects. These simulations are widely adopted worldwide due to their adaptability, research-driven development, and ability to foster deep understanding of complex scientific concepts through exploration and feedback.

3.3.2 Pedagogical Affordances of PhET Simulations

PhET simulations offer several pedagogical affordances that make them a valuable tool for teaching and learning science, particularly in abstract topics such as electricity and circuits. These affordances include interactive exploration, immediate feedback, multiple representations, and inquiry-based engagement that collectively improve learners' understanding and motivation.

One of the most significant affordances of PhET simulations is the ability to support exploration-based learning. The simulations are designed to allow learners to manipulate variables freely and observe outcomes, encouraging them to ask questions, test hypotheses, and draw conclusions. This hands-on approach fosters inquiry skills and scientific reasoning in a low-risk virtual environment (Perkins et al., 2006; Prima et al., 2018). Through repeated interactions, learners can refine their thinking and gain a deeper understanding of complex scientific ideas such as electric circuits or molecular interactions (Rahmawati et al., 2022).

Immediate feedback is another powerful feature of PhET simulations. Learners receive real-time visual responses to their actions, such as seeing how changing resistance affects current in a circuit, which helps them understand cause-and-effect relationships within scientific systems (Rahmawati et al., 2022; Perkins et al., 2006). This feedback loop not only strengthens content knowledge but also promotes active learning and retention, as learners are more likely to engage with content that responds to their inputs (Salame & Makki, 2021).

A notable strength of PhET simulations is their support for multiple representations of concepts. Learners can simultaneously engage with macroscopic, symbolic, and sub-microscopic levels of representation, an essential skill in science education (Özcan et al., 2020). For example, learners working with electric circuit simulations can visualize the flow of electrons while also viewing numerical data and symbolic notations, which reinforces their conceptual understanding from different angles (Rahmawati et al., 2022; Banda & Nzabahimana, 2021).

The simulations are also carefully designed to promote scaffolding. According to Perkins et al. (2006), PhET simulations incorporate research-based design principles that guide learners through complex content without overwhelming them. By presenting intuitive interfaces, such as sliders, graphs, and real-time animations, PhET helps learners focus on key learning goals while reducing cognitive overload.

Furthermore, PhET simulations support individualized learning. They are accessible on low-spec devices and can be paused, replayed, or adjusted to suit each learner's pace and needs. This feature is particularly helpful in under-resourced environments, such as rural schools in South Africa, where traditional lab equipment may be unavailable or unsafe to use (Olugbade et al., 2024; Banda & Nzabahimana, 2021).

Overall, the pedagogical affordances of PhET simulations, interactive exploration, immediate feedback, integration of multiple representations, and scaffolding, make them a valuable tool for enhancing science learning. These features enable learners not only to understand scientific content better but also to engage with it more deeply and independently.

3.3.3 Studies on PhET effectiveness in Physical Sciences

Several recent studies demonstrate that PhET simulations significantly enhance learners' learning outcomes in both physics and chemistry. These studies emphasize improvements in conceptual understanding, academic performance, and engagement, especially when PhET is used in well-structured instructional settings.

Olugbade et al. (2024) found that learners taught using PhET in basic science and technology achieved much higher post-test scores compared to those taught with traditional methods. The mean post-test score for the PhET group was 76.96, compared to just 23.19 for the control group. The difference was statistically significant, confirming the effectiveness of PhET in promoting deep learning and academic performance.

In physics education, Banda and Nzabahimana (2021) noted that PhET simulations helped learners gain a strong conceptual understanding of abstract phenomena such as force and motion. The simulations were especially effective in correcting misconceptions and fostering metacognitive skills. Learners learned to reason more deeply about physical concepts and could transfer knowledge to new problems.

Similarly, Pranata (2024) showed that PhET simulations significantly improved learners' understanding of geometric optics. The study reported a medium effect size of 0.62 for the PhET group, indicating that learners taught using these simulations performed better than those who received traditional instruction. The improvement was also reflected in normalized learning gains, suggesting a robust enhancement in learning outcomes.

In chemistry, Salame and Makki (2021) reported that learners using PhET simulations during General Chemistry II showed marked improvements in both understanding and attitudes towards the subject. The simulations helped learners connect macroscopic, sub-microscopic, and symbolic representations, which are often challenging in chemistry learning. Learners appreciated the visual and interactive elements and found them useful for making abstract ideas more concrete.

Watson et al. (2020) also found positive effects of PhET simulations in chemistry education. Their study showed improved conceptual understanding of pH and increased learner confidence. The collaborative nature of using PhET simulations further enhanced peer interaction and helped learners grasp challenging concepts more effectively.

Prima et al. (2018) conducted a study in a physics context where PhET was used to teach the solar system. Their results showed a significant increase in both motivation and understanding, especially when learners were allowed to explore the simulations at their own pace. The study highlighted that interactivity and visual clarity were key drivers of learner engagement and learning.

Across these studies, PhET simulations consistently emerge as powerful tools for enhancing understanding, promoting motivation, and supporting inquiry-based learning in both physics and chemistry. The evidence strongly supports their integration into science teaching to improve learner learning outcomes.

3.3.4 Benefits observed in learners

The use of PhET simulations in physics and chemistry education has been shown to enhance several aspects of learner development, particularly in conceptual understanding, motivation, and problem-solving skills. Across various studies, these interactive simulations have allowed learners to visualize abstract concepts, engage more deeply with content, and build reasoning skills through exploration and experimentation.

PhET simulations improve learners' conceptual understanding by making invisible processes visible and interactive. In their study on electric circuits, Banda and Nzabahimana (2021) found that simulations helped learners grasp complex relationships between current, voltage, and resistance more effectively than traditional methods. Learners were able to manipulate variables and observe outcomes, which led to a deeper understanding of the scientific principles involved. Similarly, Özcan et al. (2020) reported significant gains in learners' conceptual understanding of energy transformation after the integration of PhET simulations into lessons. The visual and dynamic nature of the simulations supported the learners' ability to link theoretical knowledge to practical situations.

In terms of motivation, studies consistently show that learners find PhET simulations enjoyable and engaging. Cetinkaya and Kirilmazkaya (2022) demonstrated that learners showed increased interest and willingness to participate in class activities when PhET simulations were used. The interactive features stimulated curiosity and created a learner-centred environment where learners could learn at their own pace. Perkins et al. (2006), as pioneers in the development and study of PhET simulations, also emphasized the motivational appeal of these tools. They noted that learners often spent additional time using the simulations outside of class, indicating a strong intrinsic motivation to learn through exploration.

Problem-solving skills are also positively impacted. Rahmawati et al. (2022) found that using PhET simulations to teach gas laws enhanced learners' ability to reason through problems involving pressure, volume, and temperature. Learners could test hypotheses in real-time, reinforcing the link between conceptual knowledge and problem-solving processes. In a similar vein, Pranata (2024) observed that learners using PhET to explore Newton's laws developed better strategies for analysing forces and motion. They moved from rote memorization to a more analytical approach in solving mechanics problems.

Moreover, the studies by Prima et al. (2018) and Olugbade et al. (2024) support the view that simulations foster critical thinking and facilitate active learning. Prima et al. emphasized that when learners engage with simulations, they are more likely to ask questions, discuss findings, and reflect on their learning processes. This social and reflective dimension further supports the development of problem-solving competencies. Olugbade et al. (2024) confirmed that learners using PhET simulations in chemical bonding developed more accurate mental models and improved in tasks that required higher-order thinking.

Overall, the body of evidence across these studies points to the value of PhET simulations in supporting learners’ understanding, motivation, and problem-solving abilities in both physics and chemistry. These simulations make learning more accessible and meaningful by promoting active, visual, and inquiry-based experiences.

3.5 Learner Performance in Electric Circuits

3.5.1 Common Misconceptions in Electric Circuits

Research continues to show that misconceptions about electric circuits are widespread among learners, often impeding meaningful understanding and application of core physics concepts. A common misunderstanding is that electric current is “used up” as it passes through components, especially in series circuits. Learners often believe that the current gets weaker or diminished after passing through each resistor or light bulb, which contradicts the scientific understanding that current remains constant in series circuits (Aligo et al., 2021; Özmen, 2024). This belief is rooted in everyday experiences, such as associating brightness with energy consumption, leading to the assumption that energy and current behave the same way.

Another persistent misconception involves confusing voltage with current. Learners frequently think of voltage as flowing through a circuit like current does, or they treat voltage and current as interchangeable (Güçlüer, 2020; Espera et al., 2020). This confusion may stem from the abstract nature of both concepts and the way they are presented in textbooks and classroom instruction. Voltage is a potential difference, not a flowing substance, but this distinction is often unclear to learners without concrete experiences or models.

The structure of instruction can also reinforce these misconceptions. For instance, when circuit concepts are taught in a theoretical manner without the support of real-time visualizations or simulations, learners struggle to conceptualize the invisible dynamics of electric flow. Widodo et al. (2018) highlight how learners misinterpret the function of batteries, believing they push current in an uneven or one-time manner, rather than understanding the continuous nature of electric flow. This results in learners thinking that energy is supplied in a burst and then fades, especially when lights dim in demonstration circuits.

Furthermore, Bradley et al. (2019) and Nasri (2020) found that many learners incorrectly believe that bulbs “consume” current or that larger bulbs “absorb” more electricity, failing to grasp that all components in a series circuit experience the same current. This idea is further complicated when learners are introduced to parallel circuits without first addressing their existing misconceptions from series circuits.

Incorporating effective interventions such as interactive simulations or structured inquiry activities has been shown to address and sometimes correct these misconceptions. Sambamurthy and Edgcomb (2018) argue that constructivist approaches, where learners actively test and revise their mental models, offer a promising pathway for deeper understanding. Moodley and Gaigher (2019) support this by demonstrating that learners who engage in reflective reasoning and group discussion can challenge their peers' incorrect assumptions, especially regarding current division and energy conservation.

However, the persistence of misconceptions suggests that more than corrective teaching is required. As Bauman et al. (2024) explain, misconceptions are not simply incorrect ideas but deeply held mental models formed from early intuitions and reinforced by surface-level instruction. Therefore, efforts to improve learners' understanding of electric circuits must go beyond presenting correct information, they must foster conceptual change through carefully designed interventions that surface, confront, and reconstruct learner thinking.

These conceptual misunderstandings are not limited to international contexts. In South Africa, the National Senior Certificate Diagnostic Reports consistently highlight the same patterns of misconceptions among Grade 12 Physical Sciences learners. Reports from 2018 to 2023 have noted that many learners struggle with understanding basic circuit behaviour, especially in differentiating between current and voltage, interpreting circuit diagrams, and applying Ohm's Law correctly. For example, the DBE (2021) report highlighted that many learners incorrectly reason that the current in a series circuit decreases as it moves through each component and that current splits unevenly in parallel circuits without applying scientific principles. Additionally, learners often struggle to apply Ohm's Law correctly in mixed circuit configurations and show confusion regarding internal resistance and terminal voltage. Furthermore, these reports observed that learners fail to correctly apply formulas involving internal resistance and terminal voltage – indicating a deeper problem with understanding how energy is transferred in real circuits.

These national assessments confirm that the misconceptions highlighted in research are also present in South African classrooms. They point to a need for more effective, learner-centred instructional approaches – such as interactive simulations and conceptual teaching tools – to address and rectify these deeply rooted misunderstandings.

3.5.2 Cognitive Demands of Electric Circuits Concepts

According to the Physical Sciences Examination Guidelines (DBE, 2021), the national assessment framework for Physical Sciences in South Africa places considerable emphasis on high-order cognitive levels. The guideline outlines four levels of cognitive demand: Level 1 (Recall), Level 2 (Comprehension), Level 3 (Application and Analysis), and Level 4 (Synthesis and Evaluation). Together, Levels 3 and 4 – which represent higher-order thinking - must collectively account for 50% of assessment marks in the subject. This distribution is consistent across both Physics (Paper 1) and

Chemistry (Paper 2), highlighting the DBE’s intention to foster analytical and problem-solving skills among learners. In Paper 1, which covers Physics, the same cognitive weighting applies. The expectation is that half of the paper should challenge learners to apply their knowledge to unfamiliar contexts, interpret complex data, and synthesise or evaluate information. Within this paper, the topic of Electricity and Magnetism, including electric circuits, forms a significant portion. Not only does it contribute a large share to the overall marks, but the questions often test learners’ ability to integrate theory with interpretation of circuit diagrams and mathematical calculations, which inherently demand higher-order reasoning.

Understanding electric circuits poses unique cognitive challenges due to the abstract nature of the concepts involved, the invisibility of electrical phenomena, and the symbolic representations learners must interpret. These challenges have been consistently documented in both international research and South African diagnostic assessments. One of the primary cognitive demands lies in the abstractness of electric circuit concepts. Learners must mentally simulate the behaviour of current, voltage, and resistance, phenomena that cannot be seen with the naked eye (Özmen, 2024). The invisible movement of electrons, for example, requires learners to conceptualize how energy is transferred and transformed in a system they cannot directly observe (Nasri, 2020). This difficulty is compounded when learners are expected to engage in symbolic reasoning using circuit diagrams and mathematical formulas, such as Ohm’s Law, to describe and predict circuit behaviour (Sapriadil et al., 2019; Yusuf et al., 2020).

Misconceptions rooted in these cognitive demands are persistent and well-documented. Learners often adopt intuitive but scientifically incorrect models, such as the “shared current model” in which current is thought to be split and consumed by components in a circuit (Özmen, 2024; Nasri, 2020). Others view the battery as a provider of current rather than voltage, leading to flawed reasoning in both series and parallel circuits (Nasri, 2020). These misconceptions signal a surface-level understanding that is often unaffected by traditional teaching approaches.

In the South African context, the National Diagnostic Reports confirm these learning difficulties. The reports highlight that many Grade 12 learners struggle to interpret electric circuit diagrams, apply correct circuit laws, and distinguish between concepts such as current and energy. Common errors include assuming that current is “used up” in series circuits and failing to recognize the correct behaviour of bulbs in different configurations (DBE, 2021). These findings mirror the misconceptions identified globally and affirm the abstract and representational hurdles faced by learners in understanding electric circuits.

Furthermore, Coetzee et al. (2022) found that even first-year university learners in South Africa exhibit significant gaps in conceptual understanding of direct current circuits, suggesting that these difficulties persist beyond secondary schooling. Widodo et al. (2018) also highlight that such abstract and representational demands can overwhelm learners' cognitive capacity, especially when instructional strategies do not adequately scaffold their understanding. Adding to the cognitive burden is the symbolic nature of circuit diagrams, which require learners to translate visual symbols into physical understanding (Haryadi & Pujiastuti, 2023). This translation is not intuitive for many learners, particularly those who have not had sustained exposure to hands-on or visual learning tools such as simulations or real experiments (Moodley & Gaigher, 2019). In rural and under-resourced schools, where access to laboratories is limited, these abstract demands are rarely mitigated through practical work, exacerbating conceptual confusion.

Taken together, the abstractness, invisibility, and representational complexity of electric circuits impose significant cognitive demands on learners. These demands are not incidental, they align directly with the expectations set out in the *Physical Sciences Examination Guidelines* (DBE, 2021), which allocate 50% of assessment marks to higher-order cognitive levels such as application, analysis, synthesis, and evaluation. In Paper 1 the topic of Electricity and Magnetism is heavily weighted, often requiring learners to interpret circuit diagrams, apply formulae, and reason through non-obvious relationships. Consequently, the cognitive load imposed by this topic is substantial. These challenges are not only well-documented in international research but are also reflected in consistent patterns of underperformance highlighted in South Africa’s National Diagnostic Reports. Addressing such demands requires more than traditional instruction; it calls for intentional instructional design that leverages visualizations, interactive simulations, and formative assessments to confront learners’ misconceptions and support deeper conceptual understanding (Perkins et al., 2006; Widodo et al., 2018).

3.5.3 Assessment of Learner Performance of Electric Circuits

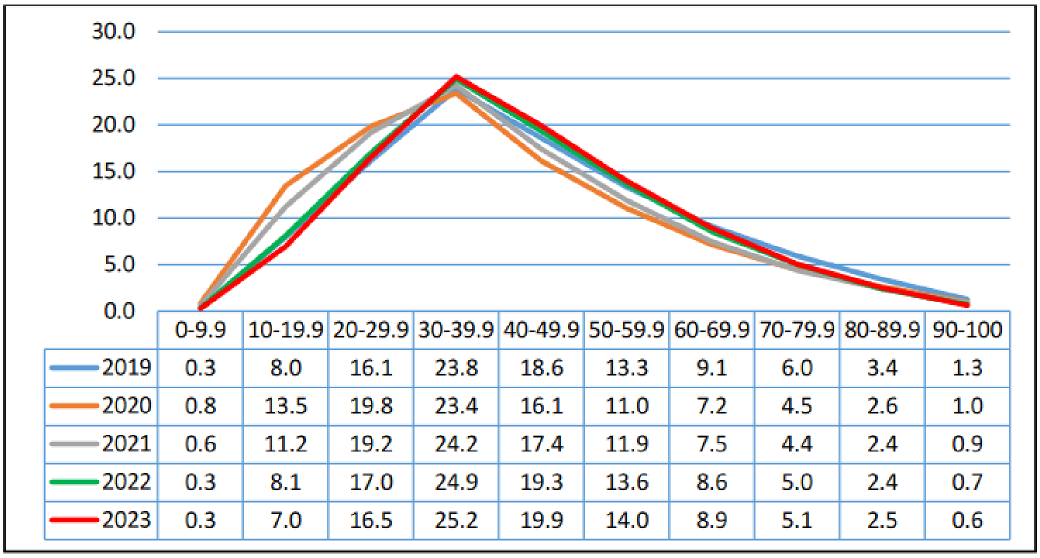
The fluctuating results in grade 12 on the topic of electric circuits have been backed by the National Diagnostic Report on learner performance, with percentages varying over the last five years; 39% in 2018, 53% in 2019, 48% in 2020, and 39% in 2021, 41% in 2022 and 42% in 2023. The tabulated data below presents the passing percentages in the field of Physical Sciences for the duration spanning from 2018 to 2022. A significant proportion of learners attain a level two score of 30%.

Table 3.1: Physical Sciences pass rates percentage from 2018 to 2023

Year	2018	2019	2020	2021	2022	2023
Learners achieved at 30% and above	74,2	75,5	65,8	69,0	74,6	76,2
Learners achieved at 40% and above	48,7	51,7	42,4	44,8	49,7	51,1

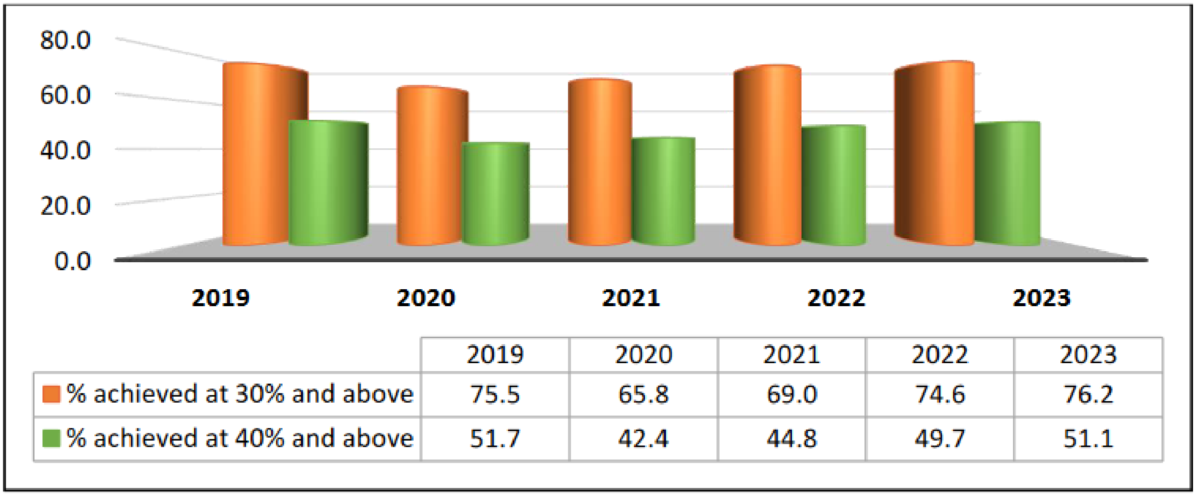
In 2018, the electric circuit question garnered a nationwide average of 39% for learners, according to the Department of Basic Education (DBE) reports. In 2019, learners studying electric circuits achieved an average score of 53% across the country. However, in 2021, their average score decreased substantially to 39%. The poor outcomes regarding electric circuits imply that South African High Schools are inadequately teaching and comprehending this topic. The application of fundamental mathematical concepts surrounding the series and parallel connection of resistors proved challenging for learners, as did forming connections between the impacts of parallel branch resistors on external resistance. Additionally, learners struggled to comprehend the relationship between electromotive and internal potential difference, as well as the concept of internal resistance. Manoeuvring and utilising formulae and equations was also an obstacle (DBE, 2018, 2019, 2020).

Despite the suggested solutions, Table 1 shows that learners are still demonstrating inadequate results in their Physical Science studies throughout the period of five years from 2018 to 2023. The diagnostic assessments suggest that learners are facing difficulties in comprehending fundamental principles of electrical circuits. Research conducted by Afra et al. (2009), Lin (2016), and Mananure et al. (2020) indicates that learners are encountering similar difficulties with key concepts across various regions of the world. The graphical representations in Figures 1.1 and 1.2 indicate the distribution of performance and overall achievement rates among South African learners in the subject of Physical Sciences over the period from 2019 to 2023. The graphical representation illustrates that the majority of learners achieved at an average between 30% and 40% in Physical Sciences during the specified years, with no notable improvement in the number of high-scoring learners over the specified years.



	0-9.9	10-19.9	20-29.9	30-39.9	40-49.9	50-59.9	60-69.9	70-79.9	80-89.9	90-100
2019	0.3	8.0	16.1	23.8	18.6	13.3	9.1	6.0	3.4	1.3
2020	0.8	13.5	19.8	23.4	16.1	11.0	7.2	4.5	2.6	1.0
2021	0.6	11.2	19.2	24.2	17.4	11.9	7.5	4.4	2.4	0.9
2022	0.3	8.1	17.0	24.9	19.3	13.6	8.6	5.0	2.4	0.7
2023	0.3	7.0	16.5	25.2	19.9	14.0	8.9	5.1	2.5	0.6

Figure 3.1 Performances distribution curves 2019-2023 in Physical Sciences (DBE,2024)



	2019	2020	2021	2022	2023
🟧 % achieved at 30% and above	75.5	65.8	69.0	74.6	76.2
🟩 % achieved at 40% and above	51.7	42.4	44.8	49.7	51.1

Figure 3.2 Overall achievement rates 2019-2023 in Physical Sciences (DBE, 2024)

3.6 Teaching Challenges in Under-resourced Contexts

3.6.1 Definition of Under-resourced schools

In South Africa, under-resourced schools are typically defined by their limited access to physical infrastructure, teaching resources, and qualified personnel, conditions that are widespread in rural communities. These schools often lack basic facilities such as laboratories, libraries, and functional classrooms, and they operate with minimal access to modern technology or reliable electricity and sanitation. Du Plessis and Mestry (2019) emphasize that rural schools face severe physical challenges, including deteriorating buildings, limited or no access to running water, and the absence of science laboratories, which are essential for effective teaching and learning. Teachers in these contexts often teach multiple grades or subjects in the same classroom without adequate support or resources, which compromises curriculum delivery and learner engagement.

The Tubatse Circuit, located within the Sekhukhune District in Limpopo Province, stands as a stark example of such an under-resourced educational environment. The district is repeatedly identified as one of the most underperforming in Limpopo, particularly in Physical Sciences. Studies show that Tubatse schools face compounded difficulties such as a lack of qualified teachers, inadequate laboratory equipment, and poor infrastructure, which hinder both teaching quality and learner performance (John, 2019; Soyikwa & Boateng, 2024). Soyikwa and Boateng (2024) further highlight that learners in such rural areas often have minimal exposure to real-world science applications due to resource scarcity, which directly affects their conceptual understanding. Similarly, Baloyi et al. (2023) stress the critical shortage of skilled Physical Science teachers and effective school leadership in these regions, contributing to systemic educational disadvantages.

In addition to infrastructure and human resource constraints, the socioeconomic realities of the community also play a crucial role. Parents often have limited education and cannot contribute financially or materially to school needs, making it difficult for schools to acquire even the most basic supplies (du Plessis & Mestry, 2019). The resultant effect is a cycle of low learner performance and teacher demotivation. Tubatse, as a microcosm of these broader national challenges, encapsulates the acute resource gaps that hinder effective science teaching in rural South Africa. This context shows the importance of investigating and implementing innovative, low-cost, and scalable interventions tailored to these realities. Therefore, the need to address teaching challenges in under-resourced settings like Tubatse Circuit is not just a local concern, it reflects national patterns of inequality and requires urgent, context-specific educational strategies.

3.6.2 Specific challenges in science teaching

As a Physical Sciences teacher in the Tubatse Circuit, I have experienced first-hand the immense challenges of teaching science in an under-resourced rural setting. Schools in this region face serious limitations that affect how learners experience and engage with science content. The lack of functional laboratories, textbooks, and up-to-date teaching materials makes it difficult to conduct meaningful practical work and reinforces teacher-centred, lecture-based methods. Soyikwa and Boateng (2024) highlight that such shortages are a common feature in rural South African schools, where learners often engage with abstract concepts without the benefit of hands-on experimentation.

These challenges are compounded by the large class sizes that are common in rural schools, which hinders individualized support and meaningful participation in science activities. In the Tubatse Circuit, it is not unusual for a Physical Sciences teacher to teach multiple grades and subjects, often without specialized training, like me I teach Physical Sciences in grades 10, 11 and 12 also teach Technology in grade 8 and 9 while I have not specialization in Technology. This is echoed by John (2019), who points out that many rural schools assign Physical Sciences teaching to teachers with no subject specialization, sometimes even to those with only a matric certificate or to unqualified learner teachers.

The impact of these conditions on teaching is stark. Teachers are expected to deliver complex and abstract topics, such as electricity and magnetism, without the resources, training, or time to properly scaffold learners' understanding. Nkanyani et al. (2023) confirm that in many rural schools, professional development for teachers is either lacking or completely absent, leaving teachers to rely on outdated teaching strategies that fail to spark learner curiosity or support deeper learning. In these environments, effective integration of digital tools, such as simulations or visualizations, is nearly impossible due to unreliable electricity, non-functional ICT equipment, or a lack of training.

Moreover, the district's prioritization of urban, better-performing schools means rural schools like those in Tubatse are often overlooked for maintenance, upgrades, or targeted support. This systemic neglect is felt in the everyday experiences of teachers who struggle to engage learners in meaningful science learning amidst broken infrastructure and minimal external support. Baloyi et al. (2023) argue that this imbalance results in a deeply unequal two-tier education system, where only well-resourced schools are positioned to produce quality outcomes.

Taken together, these realities point to a pressing need for localized and context-specific interventions. This study, situated in my own classroom in the Tubatse Circuit, seeks to explore how resource-light, yet conceptually rich tools, like PhET simulations, can be leveraged to overcome some of these challenges.

3.6.3 Digital divide and simulations use

In the Tubatse Circuit schools continue to face major setbacks in adopting digital tools for science teaching due to systemic infrastructural and socioeconomic challenges. As someone who has taught Physical Sciences in this circuit, I have witnessed firsthand how the absence of devices, erratic electricity supply due to “loadshedding”, and weak connectivity widen the educational divide, making the integration of digital tools like simulations difficult.

While PhET interactive simulations have been praised for transforming science learning through virtual experimentation and visualization (Mars et al., 2022), their impact in settings like Tubatse remains constrained by broader structural inequalities. These simulations, though freely accessible and user-friendly, rely on basic infrastructure such as electricity and stable internet, which are unreliable in many rural schools. Mthanti (2023) reports that South Africa faced severe load-shedding in 2023, with most regions, particularly rural ones, experiencing daily power outages. These outages directly interrupt access to digital learning platforms and severely limit the consistent use of simulations in science lessons.

Moreover, access to appropriate devices remains highly unequal. Most learners in the Tubatse Circuit do not own laptops or tablets, and many rely on shared or outdated smartphones that are not always compatible with educational platforms. Kavai and Nyamupangedengu (2021) found that limited access to devices and network connectivity not only reduced opportunities for interaction but also stifled learners' engagement and collaborative learning, which are essential for inquiry-based approaches encouraged in science simulations.

Connectivity further compounds the problem. Even where learners possess devices, lack of stable internet access, whether due to cost or poor infrastructure, hinders the effective implementation of simulations. John (2019) highlights that many schools in rural South Africa are digitally disconnected, and teachers themselves often have limited digital pedagogical training, which affects how they implement tools like PhET simulations.

Despite these challenges, simulations remain a promising intervention. Osman and Kriek (2021) showed that, when implemented with adequate support, PhET simulations significantly enhanced learners' understanding of electric circuits, particularly in contexts where physical lab equipment was unavailable. Yet their study also emphasized the precondition of access to devices and electricity for effective usage.

Interestingly, while rural learners are often immersed in digital culture through social media and mobile games, these informal digital experiences are not aligned with the formal schooling system. Tieken and Montgomery (2021) argue that this misalignment limits the pedagogical potential of digital technology in rural classrooms. Teachers tend to stick to traditional methods due to lack of support, which leaves learners disconnected from more engaging, technology-supported learning environments.

Therefore, in rural circuits like Tubatse, the problem is not simply the absence of technology, but a systemic digital divide characterized by poor infrastructure, lack of resources, and digital exclusion. For digital simulations to be used effectively, we need coordinated efforts, such as investment in infrastructure, affordable internet, device provision, and teacher training, to ensure that technology-enhanced learning is not a privilege of urban schools, but a right accessible to all learners across South Africa.

3.6.4 Teacher capacity and adaptation

As a Physical Sciences teacher in the Tubatse Circuit , a rural, under-resourced area marked by overcrowded classrooms and limited access to laboratory facilities , I have directly experienced the significant challenges that come with implementing technology-enhanced teaching. The success of science teaching in such contexts is deeply tied to the teacher's capacity to adapt pedagogically and use technology confidently, despite prevailing constraints. However, this capacity is often undermined by systemic challenges such as poor infrastructure, limited professional development, and minimal exposure to innovative pedagogical strategies.

Professional development remains a critical lever for strengthening teaching practices in rural schools. Yet, teachers in contexts like Tubatse often face professional isolation and a lack of targeted support. According to du Plessis and Mestry (2019), rural teachers struggle with poor conditions of service and limited access to career development opportunities, which contribute to low teacher retention and motivation. These teachers are expected to adapt to multiple teaching roles and unfamiliar community contexts with minimal institutional support, further compounding the stress of working in resource-scarce environments.

This strain is also evident in how teachers relate to educational technologies. As observed by Soyikwa and Boateng (2024), many teachers lack confidence in using technology, citing fear, unfamiliarity, and a lack of training as barriers. During training interventions, participants initially expressed anxiety and scepticism, but over time, as they engaged with simulations and inquiry-based tools, their attitudes shifted. They began to see technology not as a threat but as an enabler of dynamic learning. One participant likened the transformation to “unlearning fear and relearning pedagogy,” showing that structured support can cultivate confidence and new pedagogical visions.

This shift in mindset was echoed in Mars et al. (2022), where teachers undergoing simulation-based learning (SBL) training gradually moved from scepticism to embracing learner-centred pedagogies. The transition involved critically reflecting on their habitual practices, many of which they admitted were outdated and rigid. These reflective practices enabled teachers to reimagine their role, from being mere transmitters of knowledge to facilitators of meaningful learning, even in the absence of ideal resources.

In contexts like Tubatse, where digital tools are rarely integrated into everyday teaching, the potential of simulations such as PhET remains largely untapped. Osman and Kriek (2021) highlight that teachers often resort to rote instruction due to large class sizes and limited practical tools, yet these are the very environments where interactive simulations can offer the greatest value. However, without tailored professional development, teachers remain unaware or unprepared to use such tools effectively.

John (2019) further demonstrates the importance of grounding teacher education in local realities. He argues that many pre-service and in-service teachers carry forward ineffective pedagogical habits formed in their own schooling, and unless teacher training actively challenges these inherited norms, reform is unlikely. Teachers in rural areas, therefore, need not only exposure to new tools but also support in reshaping their beliefs about teaching and learning.

Moreover, the success of such transformation depends on the recognition that teaching in rural schools requires distinct competencies. Baloyi et al. (2023) emphasize that improving teacher quality in science education cannot be achieved through generalized interventions; instead, it requires targeted efforts that address the specific challenges of rural teachers, including access to digital content, peer collaboration, and culturally relevant teaching approaches. Finally, NkanyanI et al. (2023) stress the value of creating learning communities among teachers where they can share practices, receive mentoring, and collaboratively solve pedagogical challenges. Such communities are particularly vital in rural contexts where teachers often feel isolated.

3.7 Conclusion

The literature reviewed highlights the significant potential of PhET simulations to enhance the teaching and learning of abstract science topics like electric circuits. Studies consistently report improved learner engagement, conceptual understanding, and problem-solving when these tools are effectively used. However, challenges related to access, teacher preparedness, curriculum pressures, and systemic inequality remain particularly acute in rural and under-resourced contexts such as the Tubatse Circuit. National diagnostic reports confirm persistent learner misconceptions and poor performance in electric circuits, reinforcing the need for instructional strategies that combine conceptual richness with practical feasibility. Despite widespread recognition of the value of simulations, there is limited research on their actual classroom application in South Africa’s rural schools, especially in Grade 12 Physical Sciences. This study therefore responds to this gap by exploring the impact of PhET simulations on learner performance in electric circuits in the specific context of a rural Limpopo classroom, providing insight into how such tools can be meaningfully integrated into resource-constrained settings. The next chapter presents the research methodology, detailing the approach, design, and methods employed to investigate the impact of PhET simulations on Grade 12 learners’ performance in electric circuits.

CHAPTER FOUR: RESEARCH METHODOLOGY

4.1 Introduction

This chapter describes the methodological choices made to investigate the effect of PhET simulations as an educational intervention on Grade 12 learners' performance in electric circuits. It begins by explaining the positivist paradigm and the quantitative approach, which form the basis for measuring outcomes objectively and identifying causal relationships. A quasi-experimental design is then presented, detailing how the experimental and control groups were selected and how data were collected using pre-and post-tests. The chapter also explains the sampling methods, outlines the data analysis techniques (including descriptive and inferential statistics), and discusses the quality criteria that ensure the validity and reliability of the results. Finally, it describes the ethical considerations taken to protect participants' rights and maintain the integrity of the research process.

4.2 Research Paradigm

A research paradigm refers to a set of beliefs and practices that guide how research is conducted, defining what constitutes legitimate knowledge, how it can be acquired, and how it should be interpreted (Kivunja & Kuyini, 2017). It shapes the researcher's view of reality (ontology), the nature of knowledge (epistemology), and the methods for gathering and analyzing data (methodology).

The research paradigm adopted in this study is the positivist paradigm, which is grounded in the belief that knowledge is derived from empirical evidence and observable phenomena (Cohen et al., 2018). From an ontological perspective, positivism assumes that reality is objective and exists independently of human perception (Cohen et al., 2018; Scotland, 2012). Epistemologically, positivism holds that knowledge is obtained through observation, measurement, and experimentation (Creswell & Creswell, 2017; Cohen et al., 2018). This paradigm is particularly suitable for this study because it aligns with the purpose of achieving the research objectives of measuring performance outcomes objectively. The positivist approach emphasizes objectivity, measurement, and the use of quantitative methods to test hypotheses, making it an appropriate framework for this research (Creswell & Creswell, 2017). By focusing on measurable outcomes and statistical analysis (Park et al., 2020), the positivist paradigm allows for the systematic evaluation of the effectiveness of PhET simulations, which is essential for determining whether they can serve as a viable solution to the challenges faced by learners in rural schools.

To fully justify the choice of the positivist paradigm, it is important to consider alternative paradigms, such as the interpretivist and constructivist paradigms, and explain why they are less suitable for this study. The interpretivist paradigm, for example, is based on the idea that reality is subjective and shaped by individual experiences and social contexts (Merriam & Tisdell, 2015). Importantly, many scholars view interpretivism and constructivism as closely related paradigms, often referred to as the 'constructivist-interpretive paradigm' (Guba & Lincoln, 1994). Both emphasize the subjective construction of knowledge, but constructivism places stronger emphasis on how individuals build their own understanding through active engagement.

Interpretivist researchers often use qualitative methods, such as interviews and observations, to explore how people interpret and make sense of their experiences (Guba & Lincoln, 1994; William, 2024). While this approach could provide valuable insights into how learners perceive and interact with PhET simulations, it is less focused on establishing causal relationships or measuring outcomes, which are central to this study's objectives (Creswell & Creswell, 2017). For instance, interpretivist research might explore how learners feel about using the simulations or how they interpret the visual representations, but it would not provide the quantitative evidence needed to determine whether the simulations improve performance. In contrast, the positivist paradigm is better suited to this study because it allows for the objective measurement of performance outcomes and the testing of hypotheses, which are essential for evaluating the effectiveness of an educational intervention (Park et al., 2020).

Similarly, the constructivist paradigm, which emphasizes the active construction of knowledge through interaction with the world, is not the best fit for this study (William, 2024). Constructivist researchers often use qualitative or mixed methods to explore how individuals build their understanding through experiences and social interactions (Merriam & Tisdell, 2015).

While this paradigm aligns with the interactive and inquiry-based nature of PhET simulations, it is less focused on objective measurement and hypothesis testing (Creswell & Creswell, 2017). For example, constructivist research might explore how learners develop their understanding of electric circuits through hands-on experimentation with the simulations, but it would not provide the quantitative data needed to measure the impact of the intervention on performance (Cohen et al., 2018). In contrast, the positivist paradigm prioritizes empirical evidence and statistical analysis (Park et al., 2020), making it more suitable for a study that seeks to determine whether the use of PhET simulations leads to measurable improvements in learners' performance.

It is important to recognize that four common research paradigms are frequently referenced in research: positivism, interpretivism, critical theory, and pragmatism (Creswell & Creswell, 2017). Each offers a unique perspective on reality, knowledge, and methodology, but the choice of paradigm must align with the research objectives. The positivist paradigm is the most appropriate choice for this study because it aligns to measure the impact of PhET simulations on learners' performance in electric circuits.

While the interpretivist and constructivist paradigms offer valuable perspectives on understanding learners' experiences and the process of knowledge construction, they are less suited to the study's focus on causal relationships and objective measurement. By adopting the positivist paradigm, this study ensures that the findings are based on empirical evidence and rigorous statistical analysis, which are essential for evaluating the effectiveness of educational interventions in resource-constrained settings.

4.3 Research Approach

A research approach refers to the broad plan or strategy adopted by a researcher to collect, analyse, and interpret data to address the research problem and achieve the study's objectives (Creswell & Creswell, 2017). The research approach is closely aligned with the underlying paradigm of the study and guides the selection of methods and techniques used during the investigation.

This study adopted a quantitative research approach to investigate the effects of PhET interactive simulations on Grade 12 learners' performance in electric circuits within the Tubatse Circuit. Grounded in a positivist paradigm, this approach emphasizes the use of empirical data and observable phenomena to establish causal relationships (Creswell & Creswell, 2017). A quantitative research approach is characterized by the collection of numerical data, objective measurement, and statistical analysis to explain phenomena, test hypotheses, or evaluate interventions (Sukamolson, 2007; Williams, 2020). By collecting and analysing quantifiable data, primarily through pre- and post-tests, the researcher aimed to produce clear, measurable evidence of the intervention's effectiveness, enabling the use of statistical analysis to validate any observed changes in learner performance (Sukamolson, 2007).

A quantitative methodology is especially suitable in educational research when the objective is to evaluate the impact of specific teaching strategies or learning tools (Williams, 2020). In this context, it facilitates the objective assessment of whether PhET simulations enhance learners' understanding of electric circuits. According to Saha (2022), quantitative research is particularly effective for testing established theories or hypotheses, aligning with this study's focus on determining whether the use of PhET simulations significantly improves learners' outcomes in electric circuits.

Although this study adopts a quantitative approach, it is important to acknowledge the alternative qualitative approach to clarify the research positioning. A qualitative research approach focuses on exploring and understanding individuals' meanings, experiences, and social contexts (Merriam & Tisdell, 2015). Qualitative approaches typically involve collecting non-numerical data through methods such as interviews, observations, and document analysis. While qualitative approaches can yield valuable insights into learners' subjective experiences and contextual factors (Merriam & Tisdell, 2015), they may not provide the same level of empirical evidence required to evaluate an intervention's effectiveness. A qualitative research approach refers to the research approach that is used by researchers to study human habits through the interviews (Creswell & Creswell, 2017). In contrast, a quantitative design offers systematic data collection from larger samples, thus enhancing the reliability and validity of the results (Cohen et al., 2018). This is especially relevant in rural educational settings, where robust, evidence-based results are needed to guide interventions aimed at addressing educational challenges.

4.4 Research Design

This study was conducted using quasi-experimental design as the research design. According to Creswell (2013), a research design is defined as a plan, structure, and strategy of investigation that gives the fundamental framework for integrating all components of research to give valuable, reliable and quality results. The aim of research design is to ensure that research questions in the specific study are answered clearly.

Quantitative research can employ several research designs, each serving different purposes depending on the research questions and practical considerations (Creswell & Creswell, 2017; Johnson & Christensen, 2020). Common designs include true experimental designs, quasi-experimental designs, and non-experimental designs such as correlational or descriptive studies (Creswell & Creswell, 2017; Cohen et al., 2018). True experimental designs involve random assignment of participants to control and experimental groups to ensure maximum internal validity (Johnson & Christensen, 2020). Quasi-experimental designs are used when randomization is not possible but comparisons between groups are still made to infer causal relationships (Cohen et al., 2018). Correlational and descriptive designs focus on identifying relationships between variables without establishing causality (Creswell & Creswell, 2017). Understanding these designs allows researchers to select the one best suited to the realities and goals of the study.

A quasi-experimental design was deemed appropriate due to the contextual constraints in the Tubatse Circuit, where random assignment of learners to different groups was not viable. Instead, existing class groupings were utilized, reflecting the non-equivalent control group design (Creswell & Creswell, 2017; Mertens, 2010). This design facilitated a comparison between an experimental group (receiving PhET simulations) and a control group (following traditional instruction), even in the absence of randomization. Consequently, the researcher could explore causal relationships within a real-world classroom setting, maintaining internal validity through the use of pre-and post-tests.

The non-equivalent control group design was well-suited to assessing the effectiveness of PhET interactive simulations on learners' understanding of electric circuits. This design involves administering pre-tests and post-tests to both the experimental and control groups, enabling the researcher to establish a baseline and measure changes in learners' performance over time. A procedure of the quasi-experimental design is illustrated below.

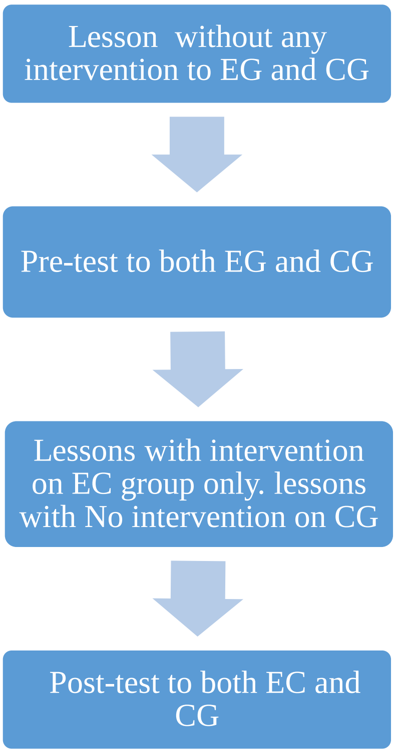


Figure 4.1 The above figure shows a procedure for the quasi-experimental design procedure.

Also, a simplified representation of the design is shown in Table 4.1.

Table 4.1: Assigning groups in a quasi-experimental design.

Group	Pre-test	Intervention (PhET Simulations	Post-test
Experimental Group (EG)	Yes	Yes	Yes
Control Group (CG)	Yes	No	Yes

Such a structured framework made it possible to evaluate the impact of the intervention by comparing learners' performance before and after the use of PhET simulations. Importantly, it also aligned with the study's quantitative objectives, ensuring that results could be analysed and interpreted using statistical methods consistent with the positivist paradigm.

4.5 Population and Sampling

4.5.1 Population

A population refers to the entire group of individuals, events, or objects that a researcher is interested in studying and to whom the findings of the study are intended to generalize (Creswell & Creswell, 2017; Shukla et al., 2020). In this study, the population comprised all Grade 12 learners enrolled for Physical Sciences in the Tubatse Circuit, Limpopo Province, South Africa. The Tubatse Circuit includes nine secondary schools that offer Physical Sciences at Grade 12 level. Across these nine schools, a total of 211 Grade 12 learners were enrolled in Physical Sciences during the time of the study. These learners formed the larger population from which the sample was drawn.

4.5.2 Sampling

Sampling is the process of selecting a subset of individuals from a larger population to participate in a research study, with the intention of drawing conclusions about the entire population (Green & Thorogood, 2018). In research methodology, sampling techniques are broadly classified into two categories: probability sampling and non-probability sampling. Probability sampling involves random selection, giving every member of the population an equal chance of being chosen, while non-probability sampling relies on non-random methods where some individuals have a greater likelihood of selection based on specific criteria (Cohen et al., 2018).

For this study, a non-probability purposive sampling technique was used. Purposive sampling involves selecting participants or groups based on specific characteristics that align with the objectives of the study (Etikan et al., 2016). Two schools were purposively selected from the nine schools in the Tubatse Circuit. The selection was based on practical considerations, such as accessibility, willingness to participate, comparable learner numbers, and the feasibility of implementing the intervention without contamination between groups.

School A, which became the Experimental Group (EG), had 57 Grade 12 learners enrolled in Physical Sciences. School B, designated as the Control Group (CG), had 45 learners in the same subject and grade. These two schools were located at a considerable distance from each other to minimize the possibility of learners sharing information about the intervention, thus reducing the risk of contamination (Mertens, 2010).

School Contexts:

- **School A (EG)**: A public rural school with limited laboratory resources, predominantly serving learners from disadvantaged backgrounds. Previous performance records indicated moderate achievement rates in Physical Sciences, with an average pass rate of approximately 50% in preceding years.
- **School B (CG)**: A similar public rural school with basic educational infrastructure but without consistent access to technological resources. This school had also recorded average Physical Sciences pass rates less than 60% over the past three years.

These contextual similarities between the two schools supported comparability, while their geographical separation helped maintain the integrity of the experimental conditions.

By selecting these two schools and implementing a quasi-experimental non-equivalent control group design, the study aimed to objectively measure the effects of PhET simulations on learners' academic performance in electric circuits.

4.6 Data Collection

Data collection refers to the systematic process of gathering and measuring information on variables of interest in a way that enables one to answer research questions, test hypotheses, and evaluate outcomes (Kabir, 2016; Creswell & Creswell, 2018). In quantitative studies, data collection aims to obtain data that can be quantified and subjected to statistical analysis. Common quantitative data collection methods include structured questionnaires, standardized tests, observations using checklists, and experimental tasks (Creswell, 2014). In this study, the researcher used standardized achievement tests administered before and after PhET simulations as an instructional intervention to collect data on learners' performance in electric circuits. This method was chosen because it provides numerical data suitable for comparison across groups, which aligns with the quasi-experimental nature of the study.

Data collection occurred during normal school hours for two weeks, and each lesson period lasted 1 hour. A total of 6 lessons were conducted with each group. The lessons focused on electric circuit concepts such as applying Ohm's Law; and clarifying terms such as emf, internal resistance, and external resistance. In line with the Annual Teaching Plan (ATP), the topic of electric circuits is allocated approximately 6–8 hours for classroom instruction.

4.6.1 The Instruments

According to Fadilah et al. (2024), instruments in a research context are tools that are used by researchers to collect data needed in research or investigation. Data collection instruments are tools that researchers choose and use to collect data in a depth way and facilitate the work program (Fadilah et al., 2024). Data collection instruments make research activities more structured and make research easier (Arikunto, 2021). Arikunto (2021) notes that research instruments commonly include tests, interviews, observations, and rating scales.

In this study, the test instrument was chosen as the primary means of data collection. Tests are particularly useful for measuring knowledge, skills, and abilities, providing quantitative data that can be analysed to determine the impact of an intervention (Fadilah et al., 2024). Specifically, two forms of the same assessment task, each containing short-answer questions and problem-solving questions, were administered at different stages of the study in the form of pre-test and post-test.

Each test consisted of 14 close-ended questions, carrying a total of 50 marks, and administered within 60 minutes. The questions included a mix of short-answer conceptual questions and quantitative problem-solving items. For instance, learners were asked to define terms such as emf and current, interpret and draw conclusions from circuit diagrams, apply Ohm's Law in various configurations, and evaluate the effects of internal resistance on terminal potential difference.

Some example items from the tests included a range of cognitive levels, from basic recall to higher-order thinking skills:

- At the **recall** level: "*State Ohm's Law in words*" – assessing ability to recall fundamental concepts.
- At the **comprehension** level: "*Explain what happens to the total resistance in a circuit with three resistors connected in parallel when another resistor is added*" – targeting understanding of how parallel circuits function.
- At the **application** level: "*Given a circuit with a battery of emf 12V and internal resistance 1Ω, calculate the current flowing when connected to a 5Ω load*" – testing ability to apply theoretical knowledge.
- At the **evaluation/synthesis** level: "*Switch S2 is now closed. How will voltmeter reading V1 be influenced? (Write down only INCREASE, DECREASE or STAYS THE SAME.) Give an explanation to your answer.*" – assessing interpretation of data and critical reasoning.

These questions were mapped to four cognitive levels defined in the CAPS taxonomy for Physical Sciences:

- CL1: Recall
- CL2: Comprehension
- CL3: Application and Analysis
- CL4: Evaluation and Synthesis

Table 4.2 below illustrates how the questions were distributed across these cognitive levels.

Table 4.2: Physical Sciences Taxonomy as defined in the CAPS (adapted from DBE, 2010)

Instrument 1.

Cognitive Level (CL)	**Content Focus**	**Number of Questions**
CL1: Recall	Definition of concepts; Ohm's Law	(2)
CL 2: Comprehension	Circuit Problems; Graphs, Ohm's Law	(6)
CL 3: Application and Analysis	Circuit Problems; Ohm's Law	(2)
CL 4: Evaluation and Synthesis	Circuit Problems; Graphs, Ohm's Law	(4)

Instrument 2

Cognitive Level (CL)	**Content Focus**	**Number of Questions**
CL1: Recall	Definition of concepts; Ohm's Law	(2)
CL 2: Comprehension	Circuit Problems; Graphs, Ohm's Law	(5)
CL3: Application and Analysis	Circuit Problems; Ohm's Law	(3)
CL 4: Evaluation and Synthesis	Circuit Problems; Graphs, Ohm's Law	(4)

By structuring questions around these cognitive levels, the tests aimed to capture not only straightforward recall but also higher-order thinking skills critical to understanding electric circuits.

4.6.2 Procedure

To minimise disruptions to the daily teaching programmes at both schools participating in the study, the respective Physical Sciences teachers, one of whom was the researcher, taught their own classes. The teachers agreed in advance to follow the same lesson plans, ensuring consistency in content, structure, and duration. The only difference was that the EG used PhET simulations, while the CG followed traditional instructional methods textbook problems, teacher-led demonstrations, and chalkboard work - without simulations. This collaborative approach allowed for a fair comparison while respecting the operational needs of each school involved the study.

The data collection process involved three phases, conducted according to the following timeline:

Phase 1: Pre-Test Administration

On 27 July 2023, learners in both the experimental and control groups wrote the pre-test under classroom conditions during their normal school timetable. The aim of this test was to determine the learners' prior knowledge and understanding of electric circuits before the intervention. Although the electric circuits topic was taught more intensively in Grade 12, both Grade 10 and Grade 11 learners had already been introduced to the fundamental concepts. Thus, the pre-test also served as a diagnostic tool to assess how well learners had retained this foundational knowledge and to identify misconceptions that may have persisted.

Each teacher marked the pre-tests from their own school. After marking, the two teachers met and cross-marked each other's learners' scripts to improve the reliability and fairness of the scoring process. This collaborative marking helped to address any biases or inconsistencies in grading.

After the marking process, feedback was provided to all learners by the researcher. This feedback was offered at both schools, and the CG's subject teacher was present during the feedback session at their school. The feedback did not involve detailed explanations of answers or corrections. Instead, it focused on general trends, common mistakes, and general encouragement. This was done intentionally to prevent the learners from being primed or coached before the intervention phase, thereby ensuring the integrity of the study’s outcomes.

Phase 2: Teaching Intervention

The teaching intervention was conducted from 28 July to 4 August 2023 over the course of six one-hour periods, as recommended by the Annual Teaching Plan (ATP) for Grade 12 Physical Sciences. The intervention took place during regular school hours to avoid disrupting the schools’ daily operations.

In the EG, the researcher used PhET’s “*Circuit Construction Kit: DC (Virtual Lab)*”. Learners built and explored virtual electric circuits in an interactive environment. The simulation includes elements such as resistors, batteries, light bulbs, voltmeters, ammeters, and wires, and provides real-time feedback on current flow and potential difference. The lessons covered:

- Constructing simple series and parallel circuits.
- Applying Ohm’s Law (V=IR) and understanding how changing resistance or voltage affects current.
- Measuring current and voltage using virtual ammeters and voltmeters.
- Differentiating between internal and external resistance and calculating total resistance in complex circuits.
- Exploring energy transfer in resistors and interpreting circuit diagrams.

For example, during the lesson on Ohm’s Law, learners in the EG used the simulation to vary the resistance and observe corresponding changes in the current, visualised as moving blue spheres. In the lesson on internal resistance, learners-built circuits that included internal resistance and observed how it affected terminal potential difference under different load conditions.

Phase 3: Post-Test Administration

The final phase of the data collection process involved administering a post-test to both the EG and CG on 5 August 2023, immediately after the completion of the six one-hour lessons on electric circuits. The test was conducted under the same classroom conditions and time allocation as the pre-test, thereby ensuring consistency in the testing environment for both groups. The post-test, like the pre-test, took a duration of 1 hour.

Both teachers independently administered the test at their respective schools during normal school periods, with the researcher present at both schools to monitor administration. After the test, each teacher marked their own learners' scripts using a shared memorandum that had been collaboratively developed and cross-checked prior to the test. To enhance marking reliability, the two teachers later came together to cross-mark a sample of each other's scripts. No feedback was given to the learners immediately after the post-test to avoid influencing the post-intervention assessment results.

4.7 Data Analysis

Data analysis in this study involved the use of both descriptive and inferential statistics to assess the effect of PhET interactive simulations on learners' performance in electric circuits. According to Kaur et al. (2018), descriptive statistics, such as percentages, means, and standard deviations, provide a clear overview by summarizing relationships among variables in an organized manner. This initial step sets the foundation for inferential statistics, which enables researchers to draw broader conclusions from the observed data (Sutanapong & Louangrath, 2015).

Accordingly, the study began by applying descriptive statistics to examine the distribution and performance of both the EG and the CG, including an analysis of pre-test and post-test scores along with measures of central tendency and variability. Building on these results, inferential statistical methods were employed to test for significance and explore potential relationships among key variables, most notably, the intervention, teaching method, and learners' cognitive levels. This two-step approach ensured a thorough examination of whether PhET simulations contributed to meaningful improvements in learner performance and cognitive engagement, thereby addressing all four guiding research objectives comprehensively (Kaur et al., 2018; Sutanapong & Louangrath, 2015).

4.7.1 Evaluating Differences in Performance Between CG And EG

On the first two research objectives, a paired-sample t-test was conducted using Statistical Package for the Social Sciences (SPSS). The t-test evaluated whether the mean differences before and after the intervention were significant for each group and whether changes in the EG differed substantively from those in the CG. The resulting p-value informed whether any observed differences in performance could be attributed to the use of PhET simulations rather than chance (Creswell & Creswell, 2017).

4.7.2 Examining the relationship between the Use Of PhET Simulations Cognitive Level of the EG

The third guiding research objective (RO3) investigated whether there was a relationship between the use of PhET simulations and the cognitive level demonstrated by learners in the EG. This relationship was examined in terms of:

- **Significance of the Relationship**: Determined via F-test, which evaluated whether the observed relationship was statistically meaningful (Alua & Thompson, 2009).
- **Strength of the Relationship**: Assessed through Pearson's r coefficient of correlation, indicating how strongly variables (PhET usage and higher-order cognitive performance) were associated.

By analysing both the significance and strength of this relationship, the study provided insights into how deeply PhET simulations might affect advanced cognitive processes, such as analysis, evaluation, and synthesis, in the context of electric circuits.

4.7.3 Examining the relationship between the use of conventional teaching and learning methods and the cognitive level of CG

Lastly, the fourth guiding research objective (RO4) explored whether there was a relationship between the conventional teaching and learning method used in the CG and learners' cognitive level. Similar to RO3, this inquiry involved examining:

- **Significance of the Relationship**: Through an F-test, determining whether any association between conventional instruction and cognitive level was statistically significant (Alua & Thompson, 2009).
- **Strength of the Relationship**: Using Pearson's r to gauge the degree to which traditional instruction correlated with higher-order thinking in electric circuit problem-solving.

Although the CG did not receive the PhET simulation intervention, analysing these relationships offered a comparative basis to understand whether traditional methods could similarly foster advanced cognitive abilities or if the influence of PhET was more pronounced.

4.8 Quality Criteria

4.8.1 Validity

Validity refers to the extent to which an instrument measures what it is intended to measure (Creswell, 2014). To ensure strong content and construct validity, the researcher drew the test items for both Instrument 1 (pre-test) and Instrument 2 (post-test) from the NSC Physical Sciences Paper 1 examinations of November 2008 and November 2019**,** respectively. These papers are quality-assured by Umalusi**,** the national assessment quality assurer, and align directly with the CAPS for Physical Sciences.

Both Instrument 1 and Instrument 2 contained questions from all four cognitive levels, allowing the researcher to capture a wide range of learner competencies. The mapping ensured that the instruments not only reflected the curriculum but also provided an opportunity to evaluate learners' conceptual depth and higher order thinking skills**, t**hereby confirming construct validity**.**

To further enhance validity, the test instruments were peer-reviewed by a panel comprising a senior education specialist, a university lecturer in science education, and an experienced Physical Sciences teacher from the same district but whose school was not part of the intervention. Their feedback confirmed that the instruments reflected curriculum expectations and were suitable for Grade 12 learners.

Content validity index was obtained as 0.93 for instrument 1 as indicated in table 1 and 0.92 for instrument 2 as indicated in table 2 below, therefore the instruments were considered to be valid.

The content validity index (CVI) was compounded using the following formula.

$$\text{CVI} = \frac{\text{number of items judged as right}}{\text{number of items on the questionnaire}}$$

TABLE 4.3: Content validity index (CVI) for survey items for instrument 1

Item	Rater 1	Rater 2	Rater 3	CVI
1	X	X	X	1.00
2	X	X	X	1.00
3	X	0	X	0.67
4	X	X	0	0.67
5	X	X	X	1.00
6	X	X	X	1.00
7	X	X	X	1.00
8	X	X	X	1.00
9	X	X	X	1.00
10	X	0	X	0.67
11	X	X	X	1.00
12	X	X	X	1.00
13	X	X	X	1.00
14	X	X	X	1.00
Overall (CVI)				**0,93**

Note: letter X indicates items of relevance and 0 indicates irrelevance.

TABLE 4.4: Content validity index (CVI) for survey items for instrument 2.

Item	Rater 1	Rater 2	Rater 3	CVI
1	X	X	X	1.00
2	X	X	X	1.00
3	X	0	X	0.67
4	X	X	X	1.00
5	X	X	X	1.00
6	X	X	X	1.00
7	X	X	X	1.00
8	X	X	X	1.00
9	0	X	X	0.67
10	X	0	X	0.67
11	X	X	X	1.00
12	X	X	X	1.00
13	X	X	X	1.00
14	X	X	0	0.67
15	X	X	X	1.00
16	X	X	X	1.00
OVERALL				**0.92**

Additionally, the coefficient Kappa was used to represent the proportion of agreements remaining after chance agreement computed using CVI is removed (Schaefer, Schmidt & Wynd, 2003). Schaefer, et al. (2003) explain coefficient kappa as an improved measure of interrater agreement over CVI's proportion agreement. Kappa was computed using the formula:

$$k = \frac{P_o - P_e}{1 - P_e},$$

The determined value (k = 1) for instrument 1 and 2 showed that the experts were in complete agreement about the relevancy of the questions to Grade 12 learners

4.8.2 Reliability

Reliability concerns whether an instrument produces consistent results under consistent conditions (Heale & Twycross, 2015). Additionally, reliability refers to the consistency and stability of an instrument in measuring what it is designed to measure (Fraenkel etal., 1993). In this study, several strategies were employed to ensure the reliability of the pre-test and post-test instruments.

First, using standardized NSC examination questions enhanced reliability by providing a familiar format that minimized confusion and promoted consistent interpretation across learners. These questions were already validated and used in national examinations, making them inherently more reliable than newly created test items.

Second, the test administration process was tightly controlled. Both the pre-test and post-test were written under formal examination conditions, during normal school hours, with the same allocated time (60 minutes). Scripts were marked independently by the respective teachers at each school, and then cross-marked to ensure scoring consistency. Any discrepancies were resolved through consensus moderation.

Third, the structure of both instruments was nearly identical in terms of item type, mark allocation, and cognitive level distribution. This ensured that observed performance differences could be attributed to the instructional intervention rather than inconsistencies in the test design.

Lastly, internal consistency reliability was verified using Cronbach's Alpha**,** yielding a coefficient of 0.71, as follows:

Table 4.5: **Indicates the reliability test results for the instrument 1**

Cronbach's Alpha	N of Items
,71	14

Table 4.6: Indicates the reliability test results for the instrument 2

Cronbach's Alpha	N of Items
,73	14

Table 4.7: Indicates the number of participants piloted for the reliability test for both instruments.

Cases	N	Percent
Valid	32	100,0%
Excluded	0	,0%
Total	32	100,0%

According to Fraenkel et al. (1993), a reliability coefficient of 0.71 or above is considered acceptable for educational research, indicating that the test items reliably measure a coherent construct.

In summary, by sourcing items from validated national examinations, ensuring curriculum alignment, implementing cross-marking, and verifying internal consistency, this study established strong evidence for both the validity and reliability of the test instruments used. These quality measures add credibility to the findings, particularly in attributing performance differences to the use of PhET simulations as an instructional tool in the teaching of electric circuits.

4.9 Ethical Consideration

4.9.1 Ethical Clearance

Before the commencement of data collection, the researcher obtained ethical clearance from the Turfloop Research Ethics Committee (TREC) at the University of Limpopo. This process involved submitting a detailed research proposal outlining the study’s objectives, methodology, and potential ethical risks, ensuring alignment with institutional and national guidelines for educational research (Rule et al., 2011).

4.9.2 Permission to Conduct Study

Upon receiving approval from TREC, the researcher sought authorization from the provincial Department of Education. Once official permission was granted, the researcher approached the school governing body (SGB) and the school principal in each participating school to secure site-specific consent. Additionally, a letter was sent to the Sekhukhune East Education District to confirm final permission to conduct the study. These steps ensured that the research was carried out with the full knowledge and agreement of all relevant educational stakeholders.

4.9.3 Assent and Informed Consent

Assent and informed consent were obtained from learners and their parents or guardians, respectively. To ensure clarity and accessibility, the consent forms were translated into Sepedi, and detailed explanations were provided regarding the study's purpose, procedures, and potential risks (Heale & Shorten, 2017). All learners were required to return signed consent forms (from parents or guardians) and signed assent forms (for the learners themselves) before they could participate. They were also informed of their right to withdraw at any point without incurring any penalties.

4.9.4 Ethical Principles

This study adhered to several key ethical principles (Rule et al., 2011):

1. **Autonomy**

    - Ensured confidentiality and anonymity by safeguarding participants' identities and restricting access to personal information.
    - Emphasized the voluntary nature of participation and avoided collecting sensitive data on the consent forms.

2. **Non-Maleficence (No Harm)**

    - Designed lessons and activities to avoid physical or emotional harm, adhering to routine classroom practices that would not endanger participants.

3. **Beneficence**

   - Provided educational benefits to all learners, including those in the CG who later received exposure to PhET simulations.
   - Maintained a commitment to sharing constructive feedback and fostering positive learning experiences.

4. **Discontinuance (Right to Withdraw)**

   - Allowed learners the freedom to opt out at any stage of the research process without negative consequences.

5. **Integrity**

   - Treated all participants equally and respectfully, without regard to gender, race, or socio-economic background.
   - Refrained from deceptive practices and ensured the research scope was communicated accurately.

6. **Respect and Dignity**

   - Encouraged learners to engage respectfully with one another and with the researcher, maintaining a supportive classroom atmosphere conducive to fair participation and dialogue.

4.10 Methodological Alignment with CTL and CTML

The research methodology in this study was guided by both CLT and Mayer’s CTML. To begin, a needs analysis was conducted to determine the learners’ prior knowledge and the complexity of the material (Raza et al., 2020). This initial step was important because it helped the researcher design instructional materials that were suitable for the learners’ specific needs (Raza et al., 2020).

Based on the information from the needs analysis, the electric circuit content was divided into smaller, more manageable segments. Each segment included clear visuals and concise explanations, following Mayer’s segmentation and coherence principles (Harskamp et al., 2007; Ginns, 2005). Over seven days, learners were introduced to different aspects of electric circuits through PhET simulations integrated into daily lessons. After each simulation, they completed targeted assessment tasks to review the new concepts, apply what they had learned, and receive immediate feedback (Harskamp et al., 2007; Ginns, 2005). This structured approach aligned with CLT, as it helped avoid overwhelming learners with too much information at once (Harskamp et al., 2007).

Throughout the lessons, learners' cognitive load was measured using both subjective surveys and objective indicators, such as performance on tasks and time spent on each activity (Ghanbari et al., 2020; Qiao et al., 2014). When signs of high cognitive load were detected, the researcher adjusted the instructional pace or added more support to ensure the learners stayed within their optimal range for germane load (Ghanbari et al., 2020; Qiao et al., 2014; Harskamp et al., 2007). By consistently monitoring and responding to learners' cognitive load, the study aimed to maintain a balance that would support effective learning and retention of electric circuit concepts (Harskamp et al., 2007).

4.11 Conclusion

In closing, the methodology outlined in this chapter provided a structured framework for examining whether an interactive simulation tool can improve learners' understanding of electric circuits. The design, rooted in a positivist, quantitative approach, ensured that outcomes would be based on measurable evidence and could be analysed through statistical methods. By carefully selecting study participants, administering well-validated tests, and following strict ethical guidelines, the researcher aimed to produce credible results that offered meaningful insights into the effectiveness of the intervention. The next chapter presents the results collected during the data collection process.

CHAPTER FIVE: PRESENTATION OF RESULTS

5.1 Introduction

This chapter presents the results of the study on the effect of PhET simulations as an instructional intervention on Grade 12 learners' performance in electric circuits. The analysis begins by examining the pre-test performance of the CG and the EG to confirm their initial equivalence. This is followed by a comparison of post-test scores to determine whether the intervention had a significant impact on the EG's results. Throughout this presentation, independent-sample t-tests and Pearson's correlation coefficients are used to address the research objectives and test the respective hypotheses.

5.2 Pre-test Results of the EG and CG

This section presents the results of the pre-test analysis, which was conducted to ensure that the EG and CG were comparable in terms of their initial knowledge and achievement levels before the intervention. The pre-test was administered to both groups to establish a baseline for comparison (Delucchi, 2019), and the results were analysed using descriptive statistics and inferential statistical tests. The results are critical for establishing the internal validity of the study, as they confirm that any differences observed after the intervention can be attributed to the intervention, specifically, the use of PhET simulations, rather than pre-existing differences (Furtak et al., 2012).

5.2.1 Raw Pre-test Scores

The raw pre-test scores indicate a range of performance levels among learners in both the EG and the CG as presented in Table 5.1 below.

Table 5.1: Raw Pre-test Scores for Experimental and Control Groups

EG Pre-test		CG Pre-test	
Learner (n=57)	**Marks**	**Learner (n=45)**	**Marks**
Learner 1	20	Learner 1	10
Learner 2	21	Learner 2	11
Learner 3	15	Learner 3	7
Learner 4	16	Learner 4	9
Learner 5	14	Learner 5	21
Learner 6	16	Learner 6	21
Learner 7	39	Learner 7	17
Learner 8	17	Learner 8	17
Learner 9	15	Learner 9	15
Learner 10	16	Learner 10	12
Learner 11	16	Learner 11	12
Learner 12	23	Learner 12	19
Learner 13	14	Learner 13	25
Learner 14	34	Learner 14	23
Learner 15	17	Learner 15	17
Learner 16	34	Learner 16	30
Learner 17	13	Learner 17	15
Learner 18	34	Learner 18	30
Learner 19	13	Learner 19	17
Learner 20	17	Learner 20	20
Learner 21	13	Learner 21	17
Learner 22	14	Learner 22	14
Learner 23	22	Learner 23	19
Learner 24	11	Learner 24	23
Learner 25	12	Learner 25	29

Learner 26	12	Learner 26	10
Learner 27	10	Learner 27	12
Learner 28	11	Learner 28	14
Learner 29	11	Learner 29	35
Learner 30	12	Learner 30	17
Learner 31	14	Learner 31	15
Learner 32	15	Learner 32	14
Learner 33	23	Learner 33	15
Learner 34	15	Learner 34	13
Learner 35	30	Learner 35	12
Learner 36	33	Learner 36	17
Learner 37	24	Learner 37	19
Learner 38	22	Learner 38	21
Learner 39	18	Learner 39	18
Learner 40	14	Learner 40	27
Learner 41	21	Learner 41	15
Learner 42	12	Learner 42	12
Learner 43	5	Learner 43	33
Learner 44	12	Learner 44	21
Learner 45	6	Learner 45	15
Learner 46	13		
Learner 47	13		
Learner 48	17		
Learner 49	9		
Learner 50	7		
Learner 51	10		
Learner 52	13		
Learner 53	30		
Learner 54	6		
Learner 55	12		
Learner 56	4		
Learner 57	2		

A preliminary examination of the raw scores suggests no distinct performance pattern between the two groups, indicating similar baseline knowledge levels. Some learners in both groups performed well, while others scored lower, reflecting the typical diversity found in a classroom setting. The statistical analysis of these scores would further confirm whether any significant differences existed at the outset. If no significant difference is found, it would mean that both groups were on an equal footing before the intervention, reinforcing the validity of subsequent comparisons (Khorsan & Crawford, 2014; Rochon et al., 2012).

5.2.2 Descriptive Statistics for Pre-test Scores

The descriptive statistics for the pre-test scores of both the EG and the CG are presented in Table 5.2 below. These statistics provide a summary of the central tendency and variability of the pre-test scores for each group (Delucchi, 2019).

Table 5.2: Descriptive Statistics for Pre-test Scores

Group	**N**	**Mean**	**Std deviation**	**Std. error Mean**
CG	45	17.62	6.45	0.96
EG	57	16.35	8.01	1.06

The raw scores revealed a wide range of individual performance levels in both groups, with some learners scoring relatively high while others scored much lower. This variation is reflected in the descriptive statistics, particularly in the standard deviations, which measure the spread of scores around the mean (Delucchi, 2019). The results shows that the CG had 45 learners with a mean score of 17.62, whereas the EG, comprising 57 learners, achieved a slightly lower mean score of 16.35. Both groups displayed moderate variability in their performance, as reflected by their standard deviations of 8.01 for the EG and 6.45 for the CG. The standard deviation measures the spread of the scores around the mean, indicating that while the CG had slightly less variability in performance, the EG showed a wider range of scores (Delucchi, 2019).

Additionally, the standard errors of 0.96 for the CG and 1.06 for the EG indicate how much each group's mean score might fluctuate if the pre-test were to be repeated under similar conditions (Delucchi, 2019). The standard error of 1.06, slightly higher than that of the CG, suggests that the estimate of the mean was still stable but with slightly more fluctuation compared to the CG.

5.2.3 Inferential Statistics: Levene's Test and Independent Sample T-test

To determine whether the differences in pre-test scores between the EG and CG were statistically significant, an independent sample t-test was conducted. However, before performing the t-test, it was necessary to assess whether the variances of the two groups were equal. This was done using Levene's Test for Equality of Variances. Levene's test evaluates whether the variances for the two groups differ substantially. In this study, the test yielded an F-value of 1.16 with a significance level (Sig.) of 0.285. Since the p-value of 0.285 is greater than the conventional threshold of 0.05, it suggests that the CG and the EG exhibit similar score variances. This means that the assumption of equal variances was met, and the independent sample t-test could proceed under the assumption of equal variances.

An independent-samples t-test was conducted to examine whether the groups' mean pre-test scores differed significantly (Akpan & Clark, 2023). The results of the t-test are presented in Table 5.3 below.

Table 5.3: Independent Samples Test for Pre-test Scores

Levene's Test for Equality of Variances	T-test for Equality of Means
F = 1.16, Sig. = 0.285	t = 0.87, df = 100, Sig. (2-tailed) = 0.389
	Mean Difference = 1.27, Std. Error Difference = 1.47
	95% Confidence Interval: Lower = -1.64, Upper = 4.19

It was necessary to assess whether the variances of the two groups were equal using Levene's Test for Equality of Variances which evaluates whether the variances for the two groups differ substantially (Zhu & Wang, 2023). As reflected in Table 7 the test yielded an F-value of 1.16 with a significance level (Sig.) of 0.285. Levene's test (F = 1.16, p = .285) indicated no significant difference in variances between the groups, satisfying the assumption of homogeneity. This means that the assumption of equal variances was met, and the independent sample t-test could proceed under the assumption of equal variances (Furtak et al., 2012).

The independent-samples t-test **(**t (100) = 0.87, p = 0.389) indicate no statistically significant difference in pre-test performance between the groups. The mean difference (1.27, SE = 1.47) had a 95% confidence interval of [-1.64, 4.19], which includes zero, suggesting that observed differences were likely due to random variation rather than a true difference in ability (Furtak et al., 2012).

The inferential statistics confirm that initial differences between the two groups were minor and statistically insignificant. While the CG had a slightly higher average score and the EG showed greater variability, these differences were not substantial enough to indicate a meaningful advantage for either group. This finding reinforces the validity of the study, ensuring that any improvements observed after the intervention can be attributed to the PhET simulations rather than pre-existing differences in learners' abilities.

5.3 Post-test Results: Comparison of the EG and the CG

This section presents the results of the post-test analysis, which was conducted to determine whether the use of PhET simulations had a significant impact on learners' performance. The post-test was administered to both the EG and the CG after the intervention period. During this period, the EG received instruction using PhET simulations, while the CG continued with traditional teaching methods.

The post-test results are analysed to address the following research objectives:

1. To investigate whether there is a significant difference in learners' performance in the EG when PhET simulations are used.

2. To investigate whether there is a significant difference in learners' performance in the CG when PhET simulations are not used.

The results are presented in three stages: raw scores, descriptive statistics, and inferential statistics, including an independent-samples t-test to compare the post-test scores of the EG and CG. The results are critical for assessing the effectiveness of PhET simulations as a teaching tool and for evaluating whether the intervention led to improved learning outcomes.

5.3.1 Raw Post-test Scores for Experimental and Control Groups

The raw post-test scores indicate a range of performance levels among learners in both the EG and the CG as presented in in Table 5.4 below.

Table 5.4: Raw Post-test Scores for Experimental and Control Groups

EG Post-test		CG Post-test	
Learner (n=57)	**Marks**	**Learner (n=45)**	**Marks**
Learner 1	28	Learner 1	5
Learner 2	31	Learner 2	13
Learner 3	17	Learner 3	7
Learner 4	30	Learner 4	23
Learner 5	18	Learner 5	19
Learner 6	18	Learner 6	29
Learner 7	15	Learner 7	31
Learner 8	16	Learner 8	25
Learner 9	35	Learner 9	20
Learner 10	40	Learner 10	3
Learner 11	25	Learner 11	12
Learner 12	21	Learner 12	13
Learner 13	19	Learner 13	18
Learner 14	35	Learner 14	9
Learner 15	31	Learner 15	7
Learner 16	33	Learner 16	25
Learner 17	38	Learner 17	21
Learner 18	38	Learner 18	14
Learner 19	12	Learner 19	11
Learner 20	23	Learner 20	21
Learner 21	13	Learner 21	11
Learner 22	14	Learner 22	6
Learner 23	21	Learner 23	5
Learner 24	23	Learner 24	10
Learner 25	26	Learner 25	28
Learner 26	34	Learner 26	19

Learner 27	40	Learner 27	5
Learner 28	37	Learner 28	7
Learner 29	44	Learner 29	5
Learner 30	46	Learner 30	7
Learner 31	33	Learner 31	12
Learner 32	28	Learner 32	27
Learner 33	17	Learner 33	31
Learner 34	44	Learner 34	17
Learner 35	45	Learner 35	23
Learner 36	37	Learner 36	30
Learner 37	17	Learner 37	31
Learner 38	21	Learner 38	29
Learner 39	29	Learner 39	14
Learner 40	41	Learner 40	17
Learner 41	40	Learner 41	29
Learner 42	39	Learner 42	35
Learner 43	18	Learner 43	15
Learner 44	23	Learner 44	12
Learner 45	29	Learner 45	16
Learner 46	33		
Learner 47	38		
Learner 48	19		
Learner 49	20		
Learner 50	36		
Learner 51	30		
Learner 52	37		
Learner 53	39		
Learner 54	16		
Learner 55	12		
Learner 56	44		
Learner 57	29		

The raw post-test scores provide an initial comparison of performance across the two groups. An examination of these scores reveals noticeable differences between the EG and CG.

The EG post-test scores demonstrate an upward shift compared to the pre-test. Many learners who initially had lower scores achieved significantly higher marks, with some reaching the 40s. This suggests that many learners in the EG experienced improvement over time. However, some variation in performance remains, with a few learners maintaining scores in the lower range.

In contrast, the CG post-test scores present a more mixed picture. While some learners improved, others remained in a similar range as in the pre-test, and a few even had lower scores than before. The highest scores in the CG did not reach the levels observed in the EG, and several learners recorded very low marks. This suggests that performance gains in the CG were not as widespread or pronounced as those observed in the EG.

A direct comparison of the pre-test and post-test raw scores shows that while both groups experienced changes in performance, the nature of these changes varies. The EG saw a more consistent increase in scores, while the CG displayed a combination of improvement, stagnation, and decline. These raw scores alone do not yet indicate the statistical significance of the changes, but they provide a clear starting point for further analysis. The next sections will present the descriptive statistics to summarize overall trends in performance and the inferential statistics to determine whether the observed differences are statistically significant.

5.3.2 Descriptive Statistics for Post-test Scores

The descriptive statistics for the post-test scores of both the EG and the CG are presented in Table 5.5 below, offering a summary of the overall performance trends.

Table 5.5: Descriptive Statistics for Post-test Scores

Group	N	Mean	Std deviation	Std. error Mean
CG	45	17.04	9.04	1.35
EG	57	28.86	10.35	1.37

The control group consisted of 45 learners, who achieved an average pre-test score of 17.62. In contrast, the experimental group, which had 57 learners, recorded a slightly lower mean score of 16.35**.** While both groups demonstrated variability in their performance, the CG exhibited a standard deviation of 6.45, indicating a moderate spread of scores around the mean. The EG, on the other hand, displayed a higher standard deviation of 8.01, suggesting that individual scores in this group were more widely dispersed compared to the CG.

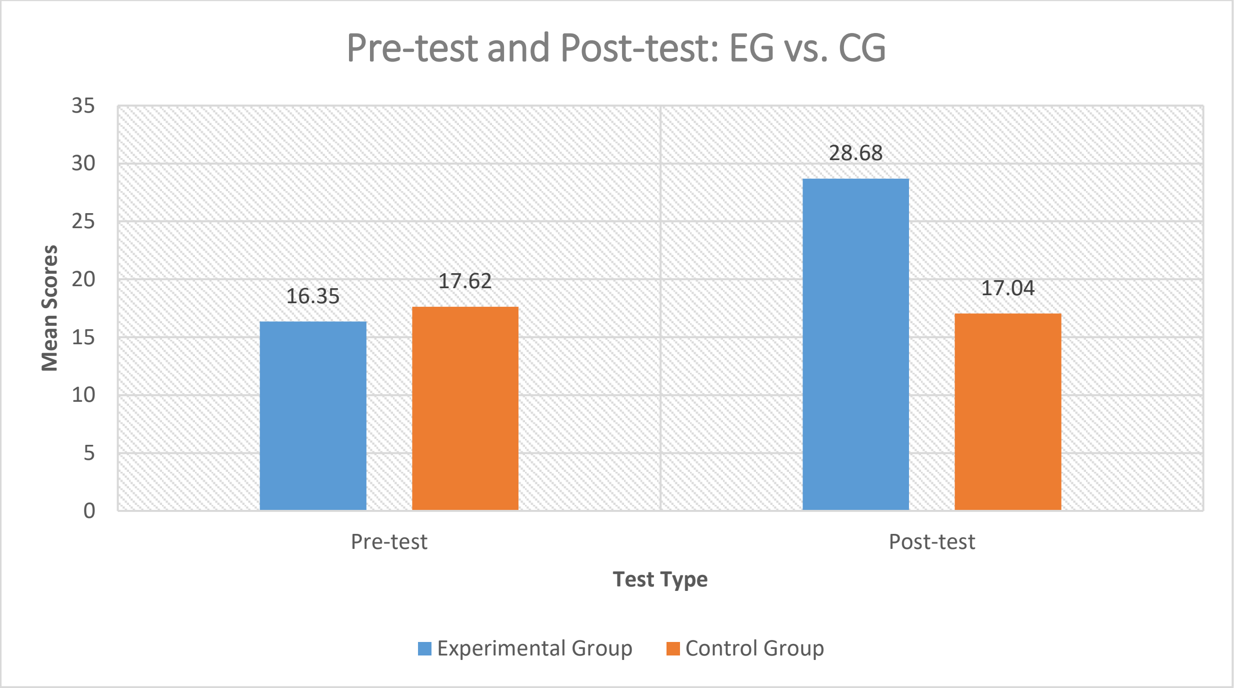
These descriptive statistics align with the raw pre-test scores, which showed that learners in both groups performed within a broad range. Some learners scored considerably lower, while others achieved notably higher marks, contributing to the observed variability. The EG had a wider range of scores, which is reflected in its higher standard deviation. This means that while some learners in the EG performed well, others scored much lower, increasing the overall spread of scores in this group. Conversely, the CG exhibited slightly more consistency, with scores clustering closer to the mean.

Furthermore, the standard errors of 0.96 for the CG and 1.06 for the EG provide insight into the precision of the mean estimates. The standard error reflects how much the sample means might fluctuate if the pre-test were to be repeated under similar conditions. Given these values, it is evident that the means for both groups are relatively stable, making them reasonable representations of the groups' initial performance levels**.**

These descriptive statistics highlight similar baseline performance between the two groups**,** with slightly greater variability observed in the EG. This information establishes a foundation for further inferential analysis, which will determine whether the differences observed in the post-test results are statistically significant.

To visually compare the mean scores for the pre-test and post-test, Figure 5.1 presents a graphical representation.

Figure 5.1: Comparison of Pre-test and Post-test Mean Scores for EG and CG



While the higher mean score of the EG suggested a potential benefit of PhET simulations, inferential statistical analysis was required to determine whether this observed difference was statistically significant.

5.3.3 Inferential Statistics: Levene’s Test and Independent Sample T-test

To determine whether the differences in post-test scores between the EG and the CG were statistically significant**,** an independent sample t-test was conducted. As with the pre-test analysis, Levene’s Test for Equality of Variances was first performed to assess whether the score variances of the two groups were comparable.

Levene’s test evaluates whether the variances for the two groups differ substantially. In this study, the test yielded an F-value of 1.18 with a significance level (p-value) of 0.280**.** Since this p-value is greater than the conventional threshold of 0.05**,** it indicates that the CG and EG had similar score variances. This finding is consistent with the descriptive statistics, which showed that while the standard deviations differed slightly between the two groups, the overall spread of scores was comparable. With the assumption of equal variances confirmed, the independent sample t-test was conducted under this assumption.

Following Levene's test, an independent-samples t-test was conducted to examine whether the mean post-test scores of the groups differed significantly. The results are presented in Table 5.6 below.

Table 5.6: Independent Samples Test for Post-test Scores

Levene's Test for Equality of Variances	**T-test for Equality of Means**
F = 1.18, Sig. = 0.280	t = -6.05, df = 100, Sig. (2-tailed) = 0.000
	Mean Difference = -11.82, Std. Error Difference = 1.95
	95% Confidence Interval: Lower = -15.69, Upper = -7.94

The t-test results reveal a t-value of -6.05 with 100 degrees of freedom and a significance level (p-value) of 0.000**.** Since the p-value is less than 0.05, it confirms that there is a statistically significant difference in post-test performance between the two groups. This means that the difference in mean scores (EG: 28.86 vs. CG: 17.04) is not due to random variation but rather reflects a true difference in the groups' performance levels.

The mean difference between the two groups was -11.82, with a standard error of 1.95**.** The 95% confidence interval for the mean difference ranged from -15.69 to -7.94, which does not include zero. This further reinforces the conclusion that a significant difference existed between the two groups after the intervention**.**

These inferential statistics align with the descriptive statistics, which showed that the EG had a higher mean post-test score and a broader spread of scores compared to the CG. The raw post-test scores also suggested an upward shift in performance for the EG, while the CG demonstrated more limited improvements. The t-test results confirm that this observed difference is statistically meaningful, indicating that the intervention had a significant impact on learner performance.

5.3.4 Rejecting the Null Hypothesis (H_{01})

The post-test results clearly show that the EG performed significantly better than the CG. The raw post-test scores reveal that many learners in the EG achieved higher marks, with several scoring in the 40s and 50s, while the CG had a much lower range of scores, with several learners scoring below 10. This upward shift in scores for the EG is reflected in the descriptive statistics, where the mean post-test score for the EG (28.86) was considerably higher than that of the CG (17.04). Additionally, the EG exhibited a broader spread of scores, indicating a wider range of performance improvement compared to the CG.

The inferential statistics confirm that this difference in performance between the two groups was statistically significant. The independent sample t-test yielded a t-value of -6.05 with a p-value of 0.000, which is far below the conventional threshold of 0.05. Since the p-value is so small, it strongly suggests that the higher performance of the EG was not due to random chance but rather a direct effect of the intervention. The mean difference of -11.82, with a 95% confidence interval ranging from -15.69 to -7.94, further supports this conclusion, as the interval does not include zero.

These results provide strong evidence to support the first research objective, which aimed to determine whether PhET simulations significantly improved learners' performance. The results indicate that the use of PhET simulations led to a meaningful improvement in scores, as seen in the higher mean and greater score variability in the EG. Additionally, the second research objective, which investigated whether traditional teaching methods were effective in the CG, is addressed by the lower mean score and more limited score variation in the CG. The results suggest that traditional methods were less effective in fostering significant performance gains.

Based on the results, the null hypothesis (H_{01}), which states that there is no significant difference in learners' performance between the EG and CG, is rejected. The statistically significant difference in post-test scores ($p < 0.05$) provides compelling evidence that PhET simulations had a positive impact on learners' performance.

Essentially, the post-test results demonstrate that the use of PhET simulations in the EG led to a statistically significant improvement in performance compared to the CG, which received only traditional instruction. The higher mean score, the wider range of improvement in the EG, and the statistically significant t-test results confirm that PhET simulations are an effective teaching tool for enhancing learners' performance.

The inferential statistics confirmed that the EG significantly outperformed the CG In the post-test, supporting the hypothesis that PhET simulations had a positive impact on learner performance. These results align with the descriptive statistics and raw scores, which suggested an upward shift in the EG's performance. This indicate that the intervention was effective in enhancing learning outcomes, warranting further exploration into the potential of PhET simulations as a teaching tool.

5.3.5 Relationship between PhET Simulations and Higher-Order Thinking

The study analysed the relationship between using PhET simulations and learners' performance on higher-order cognitive questions using Pearson's correlation coefficient ®. This statistical measure ranges from -1 to +1, where +1 indicates a perfect positive relationship, -1 indicates a perfect negative relationship, and 0 indicates no relationship. The results are presented in Table 5.7 below.

Table 5.7: Pearson's Correlation for the EG

Variable	Mean	Std deviation
Pre-test Total Score	1.000	0.913
Post-test Higher-order Cognitive Score	0.913	1.000

Key Results:

- The correlation coefficient ® = 0.913, indicating a strong positive relationship.
- The p-value = 0.000, statistically significant at the 0.05 level**.**
- Sample size (N) = 14.

These results indicate a very strong positive correlation between the use of PhET simulations and learners’ performance in answering higher-order cognitive questions. As the use of PhET simulations increased, so did learners’ ability to engage with higher-order cognitive tasks.

From the table, it is evident that there is a strong positive correlation ($r = 0.913$) between the Total Mark Test (pre-test score) and the Mark Obtained in the Post-test (higher-order cognitive score). The correlation coefficient of 0.913 is close to +1, indicating a very strong positive relationship. This means that as the use of PhET simulations increased learners’ performance on higher-order cognitive questions also improved significantly.

Additionally, the significance of the correlation was tested using a two-tailed test, which yielded a p-value of 0.000. Since the p-value is less than the conventional threshold of 0.05, the correlation is statistically significant. This means that the strong positive relationship between the use of PhET simulations and learners' ability to respond to higher-order cognitive questions is not due to random chance but reflects a true association.

5.3.6 Rejecting the Null Hypothesis (H_{03})

The strong positive correlation ($r = 0.913$) provides evidence supporting RO3. The statistical significance ($p < 0.05$) confirms that this relationship is not due to chance. Thus, PhET simulations significantly enhance learners’ higher-order cognitive skills, including analysis, synthesis, and evaluation.

The null hypothesis (H_{03}) stated that there is no strong relationship between the use of PhET simulations and learners’ ability to respond to higher-order cognitive questions. However, the results provide strong evidence to reject this null hypothesis, confirming that PhET simulations do indeed improve learners’ higher-order skills in electric circuits. Table and below illustrates the descriptive and inferential statistics, respectively, on leaners’ ability to answer HCL questions before and after use of PhET simulations.

5.3.7 Descriptive Statistics for Higher-Order Cognitive Learning (HCL) Performance in the EG

The descriptive statistics for learners' performance on higher-order cognitive learning (HCL) questions in the EG are critical for understanding the magnitude and consistency of improvement following the use of PhET simulations. Table 5.8 summarizes the pre-test and post-test results for HCL questions.

Table 5.8: Descriptive Statistics for HCL Questions (EG)

Variable	N	Mean	Std deviation	Std. Error Mean
Pre-test	57	3.25	1.64	0.22
Post-test	57	6.09	2.53	0.34

These results indicate an increase in the mean score from pre-test (3.25) to post-test (6.09), suggesting an improvement in learners' ability to answer HCL questions after using PhET simulations. These results indicate an increase in the mean score from pre-test (3.25) to post-test (6.09), suggesting an improvement in learners' ability to answer HCL questions after using PhET simulations. The table reveals a considerable increase in mean scores from the pre-test (M=3.25, SD=1.64) to the post-test (M=6.09, SD=2.53). This 89.5% improvement in mean performance emphasises the effectiveness of PhET simulations in enhancing learners' ability to tackle HCL questions.

The standard deviation increased from 1.64 to 2.53 post-intervention, suggesting greater variability in learners' post-test performance. While the higher standard deviation might indicate divergent levels of mastery among participants, it could also reflect the complexity of higher-order tasks, which naturally elicit a broader range of responses. The standard error of the mean also rose slightly (pre-test: 0.22 vs. post-test: 0.34), likely due to the expanded variability in post-test scores. Despite this, the narrow standard error of the mean values for both tests (< 0.35) confirm that the sample means are reliable estimates of the population means.

Notably, the pre-test mean score (3.25) aligns with baseline expectations for HCL tasks, which are inherently challenging. The post-test mean (6.09) not only nearly doubles the pre-test value but also demonstrates that PhET simulations facilitated meaningful skill development across the cohort. The improvement is further validated by the inferential statistics in Table 16, where the independent samples t-test ($t=-7.12$, $p<0.001$) confirms statistical significance.

5.3.8 Inferential Analysis of HCL Gains in the EG

The results of the independent samples t-test, presented in Table 5.9**,** provide evidence for the significant improvement in EG learners' higher-order cognitive learning performance following the use of PhET simulations.

Table 5.9: Independent Samples Test for HCL Questions (EG)

Levene's Test for Equality of Variances	**T-test for Equality of Means**
F = 11.02, Sig. = 0.001	t = -7.12, df = 112, Sig. (2-tailed) = 0.000
	Mean Difference = -2.84, Std. Error Difference = 0.40
	95% Confidence Interval: Lower = -3.63, Upper = -2.05

Since $p < 0.05$, the results confirm a statistically significant improvement in learners' HCL performance after using PhET simulations. The inferential analysis solidifies the conclusion that PhET simulations are not merely associated with but causally linked to marked improvements in HCL skills.

Levene's test for equality of variances yielded $F=11.02$ with a significance level of $p=0.001$, indicating unequal variances between pre-test and post-test scores. Consequently, the t-test results assuming unequal variances were interpreted. The t-test revealed a statistically significant difference between pre-test and post-test means ($t=-7.12$, $df=112$, $p<0.001$). The large negative t-value (-7.12) highlights the magnitude of improvement, with the post-test mean ($M=6.09$) substantially exceeding the pre-test mean ($M=3.25$).

The mean difference of −2.84 (95% CI: −3.63 to −2.05) highlights the practical significance of PhET simulations in electricity. The confidence interval, entirely below zero and narrow in range, reinforces the reliability of the estimated improvement. The effect size, though not explicitly calculated here, can be inferred as substantial given the t-value and sample size (N=57). These results align with the descriptive statistics in Table 16**,** which showed an 89.5% increase in mean scores, further validating the effectiveness of PhET simulations in the learning of electricity as a topic. The results decisively reject the null hypothesis (H0*H*0) and confirm that PhET simulations significantly enhance learners' ability to engage with higher-order cognitive tasks.

5.3.9 Traditional Teaching and Higher-Order Cognitive Questions

This section addresses the fourth research objective:

> To examine whether there is a strong relationship between the absence of PhET simulations and learners' ability to respond to higher-order cognitive questions in the control group (CG).

5.3.9.1 Pearson's Correlation Analysis for the CG

The relationship between traditional teaching methods (without PhET simulations) and learners' ability to answer higher-order cognitive questions was analyzed using Pearson's correlation coefficient ®. The results are presented in Table 5.10**.**

Table 5.10: Pearson's Correlation for the CG

Variable	**Pre-test Total Score**	**Post-Test Higher-Order Cognitive Score**
Pre-test Total Score	1.000	0.382
Post-Test Higher-Order Cognitive Score	0.382	1.000

Key Results:

- The correlation coefficient ® = 0.382, indicating a weak positive relationship.
- The p-value = 0.177, which is not statistically significant at the 0.05 level.
- Sample size (N) = 14.

These results indicate a weak and statistically insignificant correlation between traditional teaching methods and learners' ability to answer higher-order cognitive questions. This suggests that traditional methods have limited impact on the development of these HCL skills.

5.3.10 Lack of Evidence to Reject the Null Hypothesis (H_{04})

The weak positive correlation (r = 0.382) suggests that traditional teaching methods had a minimal effect on learners' ability to respond to higher-order cognitive questions. Since the p-value (0.177) is greater than 0.05, this relationship is not statistically significant, implying that any observed correlation could be due to random variation rather than a true association.

The null hypothesis (H_{04}) stated that there is no strong relationship between the absence of PhET simulations and learners' ability to respond to higher-order cognitive questions in the CG. The results provide insufficient evidence to reject this null hypothesis, reinforcing the notion that traditional teaching methods are less effective in fostering higher-order cognitive skills.

5.3.11 Post-test Performance in Series and Parallel Resistor Connections for HCL Questions

Table 5.11 presents individual learners' post-test scores and pre-test scores in the EG for high cognitive level (HCL) questions focusing on series and parallel resistor connections. This comparison aims to contextualize the performance improvements in the EG after the intervention (PhET simulations) against baseline performance in the CG before the intervention. These results highlight the impact of PhET simulations on learners' ability to solve complex problems requiring critical analysis and application of electrical circuit principles.

Table 5.11: Individual Pre-test and Post-test HCL Scores for Series/Parallel Resistor Questions (EG)

Learners (n=57)	Pre-test HCL Scores (Score = 12)	Post-test HCL Scores (Score = 12)

Learner 1	1	4
Learner 2	3	6
Learner 3	2	3
Learner 4	3	4
Learner 5	2	5
Learner 6	6	5
Learner 7	3	3
Learner 8	5	4
Learner 9	4	7
Learner 10	0	8
Learner 11	2	5
Learner 12	1	4
Learner 13	3	3
Learner 14	2	7
Learner 15	1	6
Learner 16	4	7
Learner 17	3	8
Learner 18	2	8
Learner 19	1	1
Learner 20	4	5
Learner 21	2	2
Learner 22	0	3
Learner 23	1	5
Learner 24	3	6
Learner 25	6	6
Learner 26	4	7

Learner 27	2	9
Learner 28	1	7
Learner 29	2	10
Learner 30	2	11
Learner 31	3	3
Learner 32	4	8
Learner 33	5	7
Learner 34	6	9
Learner 35	5	9
Learner 36	6	7
Learner 37	5	5
Learner 38	6	4
Learner 39	3	4
Learner 40	2	9
Learner 41	4	10
Learner 42	5	9
Learner 43	2	4
Learner 44	2	3
Learner 45	3	6
Learner 46	4	7
Learner 47	5	8
Learner 48	3	5
Learner 49	2	4
Learner 50	4	6
Learner 51	3	7
Learner 52	5	10
Learner 53	3	9
Learner 54	4	4
Learner 55	5	1
Learner 56	6	12
Learner 57	5	8

It is evident from the table that learners such as Learner 56 (pre-test: 6; post-test: 12/12) and Learner 30 (pre-test: 2; post-test: 11/12) achieved near perfect or perfect scores, demonstrating advanced problem-solving skills post-intervention. A few learners, such as Learner 55 (pre-test: 5; post-test: 1), experienced declines, suggesting variability in individual responses to the intervention. Most learners improved incrementally (e.g., Learner 5: 2→5; Learner 41: 4→10), indicating widespread but uneven skill development. Initially, 37 learners (65%) scored in the *low* achievement range (0–33%), while only 4 (7%) were *high* achievers (68–100%). Post-intervention, 22 learners (39%) reached the *high* achievement range, with 7 (12%) remaining in the *low* range. The largest gains occurred among high achievers, aligning with the study's observation that PhET simulations particularly benefit advanced learners.

5.3.12 Pre-test and Post-test HCL Performance in Internal Resistance and EMF for the Experimental Group (EG)

Table 5.12 shows how learners in the EG/ improved their ability to solve HCL questions on internal resistance and EMF after using PhET simulations.

Table 5.12: Individual Pre-test and Post-test HCL Scores for Internal Resistance and EMF (EG)

Learner (n=57)	HCL Post-test (10)	HCL Pre-test (10)
Learner 1	0	3
Learner 2	2	6
Learner 3	1	5
Learner 4	3	4
Learner 5	4	7
Learner 6	4	7
Learner 7	1	3
Learner 8	2	5
Learner 9	3	7
Learner 10	2	8
Learner 11	3	5
Learner 12	2	4
Learner 13	4	2
Learner 14	2	4
Learner 15	1	6
Learner 16	5	7
Learner 17	2	10
Learner 18	1	8
Learner 19	1	2
Learner 20	3	6
Learner 21	2	4
Learner 22	1	2
Learner 23	1	8
Learner 24	5	6
Learner 25	4	8
Learner 26	2	7
Learner 27	0	8

Learner 28	1	7
Learner 29	2	10
Learner 30	2	9
Learner 31	6	5
Learner 32	4	8
Learner 33	3	6
Learner 34	2	8
Learner 35	5	7
Learner 36	3	5
Learner 37	2	4
Learner 38	5	3
Learner 39	3	4
Learner 40	2	9
Learner 41	4	10
Learner 42	3	5
Learner 43	4	3
Learner 44	1	5
Learner 45	2	6
Learner 46	3	8
Learner 47	5	9
Learner 48	2	4
Learner 49	3	3
Learner 50	4	7
Learner 51	3	6
Learner 52	4	10
Learner 53	3	9
Learner 54	3	3
Learner 55	2	2
Learner 56	4	9
Learner 57	3	7

It shows from the table that 37 learners started in the low range (0–33%). Post-test, only 7 remained in this group, showing most improved. The 4 learners who started strong (pre-test mean: 70.5%) saw the largest gains, ending with a post-test mean of 78.76%**.** Learner 17 improved from 2/10 to 10/10, while Learner 41 went from 4/10 to 10/10. Even learners who started with low scores, like Learner 10 (pre-test: 2/10 → post-test: 8/10), made meaningful progress. Evidently, PhET simulations empowered most learners to achieve better scores on internal resistance and EMF.

5.4 Conclusion

The results chapter provided a detailed analysis of data collected to assess the impact of PhET simulations on Grade 12 learners' performance in electric circuits. It revealed that the experimental group (EG), which used PhET simulations, performed significantly better in the post-test than the control group (CG), showing that these simulations effectively enhance conceptual understanding and higher-order thinking skills. The strong positive link between PhET simulations and improved cognitive performance in the EG highlight the benefits of interactive learning, while the weak, insignificant relationship in the CG points to the limitations of traditional teaching methods. The next chapter will discuss these results concerning existing literature and theories, leading to the study's conclusions and recommendations.

CHAPTER SIX: DISCUSSION

6.1 Introduction

This chapter presents a discussion of the study's results, focusing on whether the use of PhET interactive simulations improves Grade 12 learners' performance in electric circuits and enhances their ability to respond to higher-order cognitive questions. The discussion builds on the study's positivist paradigm and quasi-experimental design, where quantitative data was collected using pre- and post-tests administered to both an experimental group (EG) and a control group (CG). The results are interpreted using three theoretical frameworks that guided the study: Cognitive Load Theory (CLT), the Cognitive Theory of Multimedia Learning (CTML), and Constructive Learning Theory. CLT explains how reducing unnecessary cognitive demands can support better learning. CTML emphasises the value of presenting information through both visual and verbal modes, which is a key feature of PhET simulations. Constructive Learning Theory highlights the importance of active learner participation in building conceptual understanding. This chapter also addresses the problem identified in Chapter 1—namely, learners' ongoing difficulties in mastering electric circuit concepts, as shown by national diagnostic reports and research literature. The discussion follows the order of the four research objectives and their corresponding results to ensure clarity and coherence. Each objective is discussed individually, showing whether it was achieved and what the findings mean for Physical Science teaching practice and future research.

6.2 Learner Performance Improvement in the EG using PhET Simulations

The first objective of this study aimed to determine whether the use of PhET interactive simulations significantly improved the performance of Grade 12 learners in the experimental group (EG) on the topic of electric circuits. The results presented in Chapter 5 provide compelling evidence that PhET simulations were effective in enhancing learner performance. The EG showed a substantial increase in test scores from the pre-test (mean = 15.77, SD = 4.99) to the post-test (mean = 28.86, SD = 5.46), representing a gain of over 13 marks. This improvement was statistically significant, with a paired samples t-test result of t (57) = –18.4, p = .000, indicating strong evidence against the null hypothesis (H_{01}) and supporting the alternative hypothesis (H_{a1}) that PhET simulations improved performance.

This result also aligns with the normalized gain (N-gain) of 0.49, which falls into the medium gain category according to Hake's (1998) classification. Hake's N-gain model, widely used in physics education research, classifies learning gains as low ($g < 0.3$), medium ($0.3 \leq g < 0.7$), and high ($g \geq 0.7$). The medium N-gain observed in this study suggests that the PhET intervention had a meaningful impact on conceptual understanding within a relatively short instructional period.

These findings corroborate prior research highlighting the pedagogical advantages of PhET simulations in science education. Perkins et al. (2006) argued that PhET simulations offer dynamic visualizations and interactive components that allow learners to explore abstract scientific phenomena in a hands-on manner. This interactivity is crucial when teaching topics like electric circuits, which learners often find difficult due to their abstract nature and reliance on invisible processes such as electron flow (Widodo et al., 2018). In the present study, learners were able to manipulate elements of a circuit, such as adjusting resistance or adding power sources, and observe real-time changes in voltage and current, which likely deepened their understanding and engagement.

From a theoretical standpoint, the results are well explained by CLT. According to Sweller et al. (2019), CLT suggests that learning is most effective when extraneous cognitive load is minimized, and learners are supported in constructing meaningful mental schemas. The use of PhET simulations reduced the need for learners to mentally visualize or interpret static diagrams from textbooks. Instead, learners were provided with real-time animations, which lessened cognitive effort associated with processing complex representations (Merriënboer & Sweller, 2010). This may explain the increased scores in the EG, as cognitive resources could be more efficiently directed towards intrinsic and germane load—essential for schema construction.

Furthermore, the results resonate with CTML, which posits that learners understand material more deeply when it is presented in both verbal and visual formats. PhET simulations, by their design, engage learners through dual channels—text-based instructions and visual animations—thus allowing them to make connections between the two modes of representation. This dual processing is particularly beneficial for understanding concepts like internal resistance, terminal potential difference, and current flow, which are often confusing when introduced through text and static images alone.

The observed improvement in the EG also supports the constructivist learning approach that underpins inquiry-based instruction. Constructive Learning Theory emphasizes that learners build knowledge actively through engagement with content, peer discussions, and reflection (Vygotsky, 1978; Fosnot, 2005). PhET simulations afford learners the opportunity to explore and "play" with circuit elements, formulating and testing hypotheses, which aligns with this model. The present findings echo those of Khaeruddin and Bancong (2022), who found that learners exposed to simulation-based instruction demonstrated deeper conceptual understanding and greater engagement compared to those taught through traditional methods.

In addition, the improvement in performance across different cognitive levels supports the curriculum intention of integrating both lower- and higher-order thinking. Learners in the EG showed improvement across all four levels, as presented in Table 5.6. For example, the mean score in CL2 (comprehension) improved from 4.29 to 9.00, while in CL4 (evaluation/synthesis), scores rose from 2.26 to 5.14. These results suggest that PhET simulations helped learners not only recall definitions but also apply concepts and evaluate circuit behaviour, pointing to holistic cognitive development.

These gains are consistent with the observed shifts in learner achievement in comparable studies. For instance, Banda and Nzabahimana (2021) found that dynamic simulations facilitate learners' understanding of abstract physics concepts involving Ohm's Law and series/parallel circuits through repeated manipulations and real-time feedback. Their study, which also focused on physics learning in African contexts, concluded that PhET simulations enhance learners' engagement and knowledge retention. Similarly, Taneo and Moleno (2021) demonstrated that learners who used PhET simulations in their physics classrooms showed significant gains in both conceptual and procedural knowledge. In kind, Olugbade et al. (2024) found that the use of PhET tools significantly improved learners' outcomes in science and technology subjects. Their research highlights that interactive simulations foster not only conceptual understanding but also motivation to learn. These results closely mirror the results of the present study, thereby reinforcing the conclusion that PhET simulations are a viable tool for improving science instruction in similar contexts.

Notably, the Tubatse Circuit, where this study was conducted, represents a rural and under-resourced context. The strong improvement in EG learners’ performance shows that technology-enhanced instruction can overcome some of the structural challenges faced in such environments—especially the absence of physical laboratories and apparatus (Motlhabane, 2013; Kibirige et al., 2014). hET simulations provided learners with a virtual laboratory experience, bridging the gap between theory and practical understanding. This finding aligns with the work of Rahmawati et al. (2022), who emphasised that simulations can act as low-cost alternatives in environments where equipment is unavailable.

Finally, the researcher observed that learners in the EG demonstrated increased enthusiasm and participation during lessons. Though not quantitatively measured in this study, this aligns with learner feedback reported in previous studies. For example, Saudelli et al. (2021) and Özcan et al. (2020) documented improved motivation and engagement among learners using PhET tools. Overall, the results related to Objective 1 confirm that the use of PhET simulations in the EG had a significant positive effect on learner performance. The improvement was statistically significant, educationally meaningful, and theoretically sound. These results support broader efforts to integrate technology into science education, particularly in rural and under-resourced schools.

6.3 Learner Performance in the CG: Limited Gains from Traditional Instruction

Objective 2 sought to determine whether traditional instruction alone could produce statistically significant gains in learners’ performance in electric circuits. The analysis of the pre-test and post-test results for the con CG, as presented in Tables 5.6 and 5.7, shows a limited improvement. The mean score in the pre-test was 16.49, while the post-test mean rose marginally to 17.04. This minimal increase of only 0.55 points suggests that traditional instructional methods had a negligible effect on learner performance. The paired sample t-test result for the CG was not statistically significant at the 0.05 level, confirming that the observed change was not meaningful ($t(44) = 1.98$, $p > 0.05$).

These results support the non-rejection of the null hypothesis (H_{02}), which stated that there is no significant difference in learners’ performance when PhET simulations are not used in the CG. The data align with this hypothesis, indicating that learners who received traditional instruction without the use of interactive simulations did not exhibit substantial gains in performance. The result is consistent with prior studies that have reported the limitations of conventional teaching methods in fostering meaningful conceptual understanding in Physical Sciences, especially in abstract topics like electric circuits (Widodo et al., 2018; Moodley & Gaigher, 2019). For instance, Moodley and Gaigher (2019) found that many South African learners taught using teacher-centred, textbook-driven methods struggled with persistent misconceptions about current and voltage. Similarly, Özmen (2024) observed that traditional instruction often fails to actively engage learners in conceptual change, particularly in contexts where science topics involve invisible processes and symbolic reasoning.

The marginal improvement in CG learners' scores may reflect the influence of rote learning, where leaners memorize problem-solving procedures without a deeper understanding of the underlying principles. This is particularly problematic in electric circuits, where learners are expected to interpret circuit diagrams, apply Ohm's Law, and reason about voltage and current in series-parallel circuits (DBE, 2021; Güçlüer, 2020). Without tools that allow real-time visualisation or exploration, such as PhET simulations, learners are likely to retain superficial understandings or rely on procedural recall, which limits their ability to generalise or transfer knowledge to new contexts.

Furthermore, the findings from the national diagnostic reports reinforce this concern. The DBE (2021) diagnostic report highlighted that learners frequently confuse current with voltage, struggle to analyse the effects of internal resistance, and cannot explain how potential difference changes in complex circuits. These misconceptions are not easily addressed through traditional instruction alone, especially in under-resourced schools where laboratory apparatus and hands-on experimentation opportunities are lacking (Coetzee et al., 2022; Motlhabane, 2013).

This study, conducted in the Tubatse Circuit, an area characterized by large class sizes and limited resources, further confirms that traditional methods are inadequate for significantly improving performance in electric circuits. In such contexts, the absence of technological or interactive tools exacerbates existing learning challenges, leading to a persistent gap in achievement. On the whole, the results for the CG reinforce the findings of other scholars who argue that traditional teaching approaches are insufficient for promoting conceptual understanding and learner performance in science education (Burde & Wilhelm, 2020; Aligo et al., 2021). The failure to achieve statistically significant gains in the CG highlights the need for more interactive, learner-centred approaches, such as PhET simulations, to address the challenges associated with electric circuits instruction in South African classrooms.

6.4 Effect of PhET Simulations on Higher-Order Cognitive Skills in the EG

This study also sought to determine whether learners who were taught electric circuits using PhET simulations demonstrated a stronger ability to engage with higher-order cognitive questions. This is aligned with Objective 3, which sought to examine whether a strong relationship exists between the use of PhET simulations and the ability of Grade 12 learners in the EG to respond to cognitively demanding tasks. To test this objective, the study employed Pearson's correlation coefficient to determine the strength and direction of the association between the use of PhET simulations and performance on high-level cognitive items. The analysis yielded a Pearson's correlation coefficient of $r = 0.913$, which indicates a very strong positive correlation. This result is statistically significant at $p < 0.05$, suggesting that PhET simulations played a pivotal role in strengthening learners' higher-order reasoning.

Table 5.10 in Chapter 5 presents the strength of this correlation, while Table 5.12 provides the cognitive levels breakdown. It is evident form these tables that learners in the EG were more successful in responding to CL 3 and CL 4 questions, which involve application, analysis, evaluation, and synthesis. The strong relationship indicated by $r = 0.913$ means that 91.3% of the variance in learners' ability to solve higher-order questions can be explained by their exposure to and engagement with PhET simulations. This supports the rejection of the null hypothesis ($H0_3$) and confirms the acceptance of the alternative hypothesis (HA_3), which stated that there is a strong relationship between the use of PhET simulations and learners' ability to respond to higher-level cognitive questions.

These findings echo the literature reviewed earlier. Studies by Ndihokubwayo et al. (2020) and Dantic and Fluraon (2022) found that learners' capacity to analyse and solve complex science problems improved significantly when simulations were integrated into instruction. This is because simulations present learners with cause-and-effect relationships in real time, facilitating deep processing. The ability of PhET simulations to support this kind of advanced reasoning can also be explained by the CLT and CTML. According to Sweller et al. (2019), learners experience cognitive overload when dealing with unfamiliar abstract concepts, which are common in electricity topics like internal resistance, potential difference, and electromotive force. However, PhET simulations reduce extraneous load by allowing learners to experiment in a low-risk environment where feedback is immediate and intuitive. This promotes germane processing, which is necessary for developing mental models and applying learned concepts to new scenarios (Sweller et al., 2019; Mayer, 2005).

This finding is further reinforced by Banda and Nzabahimana (2021), whose study demonstrated that learners using simulations outperformed their counterparts in cognitive reasoning, especially in physics concepts involving multiple variables. In this study, learners in the EG engaged with activities such as altering resistance values, closing switches, and observing voltmeter responses, as seen in the PhET "Circuit Construction Kit." This process of manipulating variables directly relates to constructivist learning principles, which advocate for active learner involvement (Rutten et al., 2012; Chen, 2023). Through these activities, learners in the EG were not merely absorbing facts but actively building knowledge through interaction and feedback.

In contrast to traditional teaching methods, which often encourage memorisation, the use of PhET simulations promoted analytical and reflective thinking. Learners had to predict, observe, explain, and justify their answers, especially in questions such as: *“Switch S2 is now closed. How will voltmeter reading V1 be influenced? (Write down only INCREASE, DECREASE or STAYS THE SAME.) Give an explanation to your answer.”* These types of questions, included in both instruments are consistent with CL 4 (Evaluation and Synthesis) and challenge learners to reason based on an understanding of circuit behaviour, rather than follow rote procedures.

This progression in learner responses aligns with curriculum expectations in the CAPS for Physical Sciences, which call for learners to engage with scientific processes that involve interpretation, problem-solving, and explanation (DBE, 2011). These results therefore suggest that simulation-based learning does not just improve conceptual understanding but equips learners with the competencies required for success in the 21st century, such as critical thinking, synthesis, and transfer of knowledge to unfamiliar contexts. Importantly, the observed improvement in high-level reasoning was not limited to a few learners in the EG. As reported in Table 5.11, most learners demonstrated progression from lower levels (CL1 and CL2) to higher cognitive levels (CL3 and CL4), providing strong evidence that the PhET intervention enhanced the overall cognitive profile of the cohort. This is consistent with the study of Prima et al. (2018), which showed that the use of simulations improved learner engagement across all Bloom’s levels, including analysis and synthesis. Moreover, Inayah and Masruroh (2021) showed that learners exposed to PhET-based laboratory simulations outperformed their peers in identifying variables, evaluating cause-effect relationships, and drawing accurate conclusions from scientific phenomena.

Given the above, the results of this study reinforce the assertion that interactive simulation-based instruction is essential not only for knowledge acquisition but for nurturing the kind of analytical and evaluative thinking required in science learning. Learners in the EG were more inclined to justify their responses, identify interdependencies within circuits, and reflect on variable changes — all indicators of deeper cognitive engagement. Altogether, the strong positive correlation between the use of PhET simulations and performance on higher-order questions confirms the transformative potential of simulation-based learning. The study’s results uphold international findings and extend them to a South African, rural context. The successful application of simulations in such settings suggests that well-designed digital tools like PhET can bridge the cognitive and resource gaps in underperforming and under-resourced schools, enabling all learners to meet the rigorous cognitive demands of the science curriculum.

6.5 Traditional Instruction and Higher-Order Cognitive Performance in the CG

This section addresses Objective 4, which sought to examine whether there is a strong relationship between the absence of PhET simulations and the ability of learners in the CG to respond to higher-order cognitive questions. To investigate this, the study computed a Pearson correlation coefficient to measure the strength of the association between traditional instruction and learners’ performance on high-cognitive-level questions. The analysis revealed a weak positive correlation of $r = 0.382$, suggesting only a modest link between the CG’s instructional approach and their ability to engage with complex problem-solving or critical reasoning tasks.

This result supports the rejection of the null hypothesis (H_{04}) and the acceptance of the alternative hypothesis (HA_4): there is a significant relationship—though weak—between the absence of PhET simulations and learners' limited ability to respond to higher-level cognitive questions. It confirms that the traditional instructional approach employed in the CG may not adequately promote the development of higher-order thinking.

These findings are consistent with prior research. Studies such as those by Dantic and Fluraon (2022) and Taneo and Moleno (2021) demonstrate that traditional teacher-centred approaches often fail to challenge learners cognitively. They tend to emphasise rote learning and algorithmic problem-solving rather than deep conceptual understanding. Consequently, learners may acquire basic factual knowledge but struggle with tasks requiring interpretation, evaluation, and synthesis of information which are skills aligned with higher cognitive levels as outlined in the CAPS Physical Sciences taxonomy (DBE, 2011).

The weak correlation observed in the CG points to a critical limitation of instruction that does not incorporate interactive or inquiry-based tools. Learners in this group were taught using chalk-and-talk strategies, textbook examples, and static diagrams. While this approach might be sufficient for lower-level cognitive demands such as recalling definitions or solving standard resistor problems, it does not provide the necessary scaffolding to deal with abstract and integrated concepts like internal resistance, terminal potential difference, or complex electric circuits.

Table 5.13 in the Chapter 5 showed that CG learners had difficulty with questions that required analysis or evaluation. Performance on such items remained weak compared to the EG. The Literature Review showed that South African learners, particularly those in under-resourced schools, often face challenges when learning abstract topics like electric circuits due to a lack of laboratories, teaching aids, and adequately trained teachers (Kibirige et al., 2014; Motlhabane, 2013). The CG in this study represented such a context. Without access to PhET simulations or practical experimentation, learners relied solely on verbal descriptions and textbook diagrams. This limited exposure appears to have restricted their conceptual growth and problem-solving development.

Moreover, the theoretical framework underpinning this study further explains this outcome. According to CLT, learners must be able to allocate cognitive resources efficiently between managing new information (intrinsic load), avoiding distractions (extraneous load), and constructing meaningful understanding (germane load) (Sweller et al., 2019). Traditional instruction often increases extraneous load by presenting abstract and symbolic content without sufficient supports (Merriënboer & Sweller, 2010). This cognitive overload likely hindered CG learners from transferring knowledge to novel contexts or reasoning through conceptual changes within circuits.

In contrast, the CTML by Mayer (2005) suggests that learners learn more effectively when information is presented using words and visuals rather than words alone. The CG's instruction lacked this dual modality. Unlike learners in the EG, they were not able to interact with visual simulations that demonstrated, for instance, how internal resistance affects terminal voltage, or how current redistributes when a switch is closed. As a result, their capacity to engage with integrated reasoning questions was significantly diminished.

Furthermore, when compared to the findings for the EG, the CG's outcome raises broader implications. While the CG showed some limited improvement from pre- to post-test (mean increase: 13,09 to 17,04), this progress was mostly in CL1 and CL2 questions (Recall and Comprehension). As reported in Table 5.13, fewer CG learners advanced to CL3 or CL4. This highlights the inadequacy of traditional methods in supporting the cognitive demands expected in Grade 12 electric circuit assessment. This section has shown that while traditional teaching methods provide a foundation for basic conceptual knowledge, they fall short in equipping learners to respond to higher-order tasks. The weak positive correlation of r = 0.382 between traditional instruction and cognitive performance confirms that the CG's approach had limited effectiveness in fostering the reasoning, analysis, and evaluation skills needed in science education. This finding shows the importance of incorporating simulation tools like PhET in science classrooms, especially in rural and resource-constrained schools, to help bridge the gap in cognitive achievement and prepare learners for the demands of the national curriculum and real-world scientific reasoning.

6.6 Conclusion

This chapter discussed the results of the study in light of the research objectives, theoretical framework, and literature reviewed in Chapter 3. The purpose was to examine the effect of PhET interactive simulations on Grade 12 learners' performance and their ability to engage with higher-order cognitive questions in electric circuits. Each objective was addressed sequentially to ensure coherence and alignment with the results presented in Chapter 5.

With respect to Objective 1, the study found a statistically significant improvement in the performance of learners in the experimental group (EG) after the use of PhET simulations, with a mean increase from 13.09 to 28.86 and a paired t-test value of $t(57) = 14.7$, $p < 0.05$, confirming the effectiveness of the simulations in supporting learning of electric circuits.

For Objective 2, the results showed a much smaller performance increase in the control group (CG), where traditional teaching was used, with a mean increase from 13.09 to 17.04 and $t(44) = 5.69$, $p < 0.05$, indicating a significant but less impactful improvement compared to the EG.

In relation to Objective 3, a very strong positive correlation was observed between the use of PhET simulations and learners' ability to respond to higher-order questions in the EG ($r = 0.913$), showing that simulation-supported instruction effectively promotes deeper conceptual understanding and cognitive reasoning.

Regarding Objective 4, a weak positive correlation ($r = 0.382$) was found between traditional instruction and the ability of CG learners to engage with higher-order questions, highlighting the limitations of conventional methods in supporting high-level cognitive engagement in the context of electric circuits.

Collectively, these results provide an empirical support for integrating PhET interactive simulations into Physical Science instruction, particularly in under-resourced rural contexts such as the Tubatse Circuit. The chapter confirmed that the use of simulations not only improves general performance but also enhances learners' capacity to tackle cognitively demanding tasks, in line with Constructivist Learning

Theory, Cognitive Load Theory, and the Cognitive Theory of Multimedia Learning. The results further contribute to addressing the persistent underperformance of South African learners in electric circuits as highlighted in national diagnostic reports.

The next chapter concludes the study by summarising key insights, highlighting implications for teaching practice and curriculum support, and offering recommendations for future research.

CHAPTER SEVEN: CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

This chapter summarizes the key results of the study, discusses their implications, and provides recommendations for teachers, policymakers, and researchers. The study investigated the effect of PhET interactive simulations on Grade 12 learners' performance in electric circuits within the Tubatse Circuit, a rural and resource-constrained setting in South Africa. The results reveal significant improvements in learners' conceptual understanding, higher-order cognitive skills, and overall academic performance, highlighting the potential of PhET simulations to address persistent challenges in science education. This chapter also acknowledges the limitations of the study and suggests directions for future research.

7.2 Significance of the study

This study aimed to contribute both theoretically and practically to the teaching and learning of electric circuits in Grade 12 Physical Sciences. By examining the role of PhET interactive simulations, the research provides new insights that can benefit scholars, teachers, and policymakers.

7.2.1 Theoretical Significance

Theoretically, this research adds to the growing body of knowledge on how technological tools, particularly interactive simulations, can influence conceptual understanding and cognitive development in science education. While prior studies have explored the value of simulations in enhancing learning outcomes, there is a relative shortage of research focusing specifically on electric circuits within the South African context, especially in rural schooling contexts such as the Tubatse Circuit. By investigating the effectiveness of PhET simulations, this study broadens existing literature on constructivist-based teaching approaches, offering new perspectives on how learners acquire higher-order thinking skills when engaging with interactive, visual learning experiences. The study’s results may also inform future theory-building in educational technology, science pedagogy, and curriculum design.

7.2.2 Practical Significance

From a practical standpoint, this study offers actionable insights for teachers, school administrators, and education officials who aim to enhance learners’ performance in Physical Sciences. If results show that PhET simulations improve learners’ understanding and skills in electric circuits, teachers may adopt or increase their use of these simulations in the classroom. This approach can be particularly beneficial in schools with limited laboratory equipment, as simulations can serve as cost-effective and accessible alternatives to traditional hands-on experiments. Furthermore, school administrators and policymakers can draw on these results to allocate resources more effectively, integrate simulation-based instruction into professional development programs, and develop policies that encourage the use of innovative, technology-driven teaching methods. Ultimately, the practical significance of this research lies in its potential to improve learners’ academic performance, increase their motivation to study science subjects, and better prepare them for advanced studies or careers in science and engineering.

7.3 Conclusions

The study concludes that PhET interactive simulations are a highly effective tool for improving Grade 12 learners' performance in electric circuits, particularly in rural and resource-constrained settings. By providing a dynamic, hands-on learning environment, PhET simulations enable learners to visualize and manipulate abstract concepts, reducing cognitive barriers and fostering deeper understanding. The simulations also promote higher-order cognitive skills, such as analysis, evaluation, and problem-solving, which are critical for success in science education and beyond. The study also highlights the practical benefits of PhET simulations in addressing resource constraints, such as limited laboratory equipment and underqualified teachers. By providing a virtual alternative to traditional experiments, PhET simulations ensure that learners in under-resourced schools have access to high-quality science education.

7.4 Limitations of the Study

While the study provides valuable insights, it is not without limitations. The use of intact classroom groupings and the lack of random assignment may have introduced confounding variables that affected the results. A true experimental design with random assignment would strengthen the validity of the results. The study focused exclusively on Grade 12 learners in the Tubatse Circuit, which may limit the applicability of the results to other contexts or grade levels. The reliance on pre-and post-tests to measure learner performance may not capture the full range of learners' experiences and perceptions. Incorporating qualitative methods, such as interviews or observations, could provide a more comprehensive understanding of the impact of PhET simulations. Finally, the study was conducted over a relatively short period, which may not fully capture the long-term effects of using PhET simulations. A longer intervention period could provide more robust evidence of their effectiveness.

7.5 Recommendations

Based on the results of this study, future research should explore the long-term impact of PhET simulations on learners' performance and retention of knowledge through longitudinal studies, while also investigating their broader applicability in other science topics such as mechanics, thermodynamics, and chemistry. Additionally, qualitative studies should be conducted to complement quantitative results by exploring learners' and teachers' perceptions of using PhET simulations in the classroom. Research should also focus on identifying best practices for integrating PhET simulations into the curriculum, including teacher training, lesson design, and assessment strategies, as well as examining the scalability of these simulations in large-scale educational systems, particularly in resource-constrained settings, to assess their feasibility and impact on a broader scale. These directions for further study will help deepen our understanding of how PhET simulations can be effectively utilized to enhance science education outcomes across diverse contexts.

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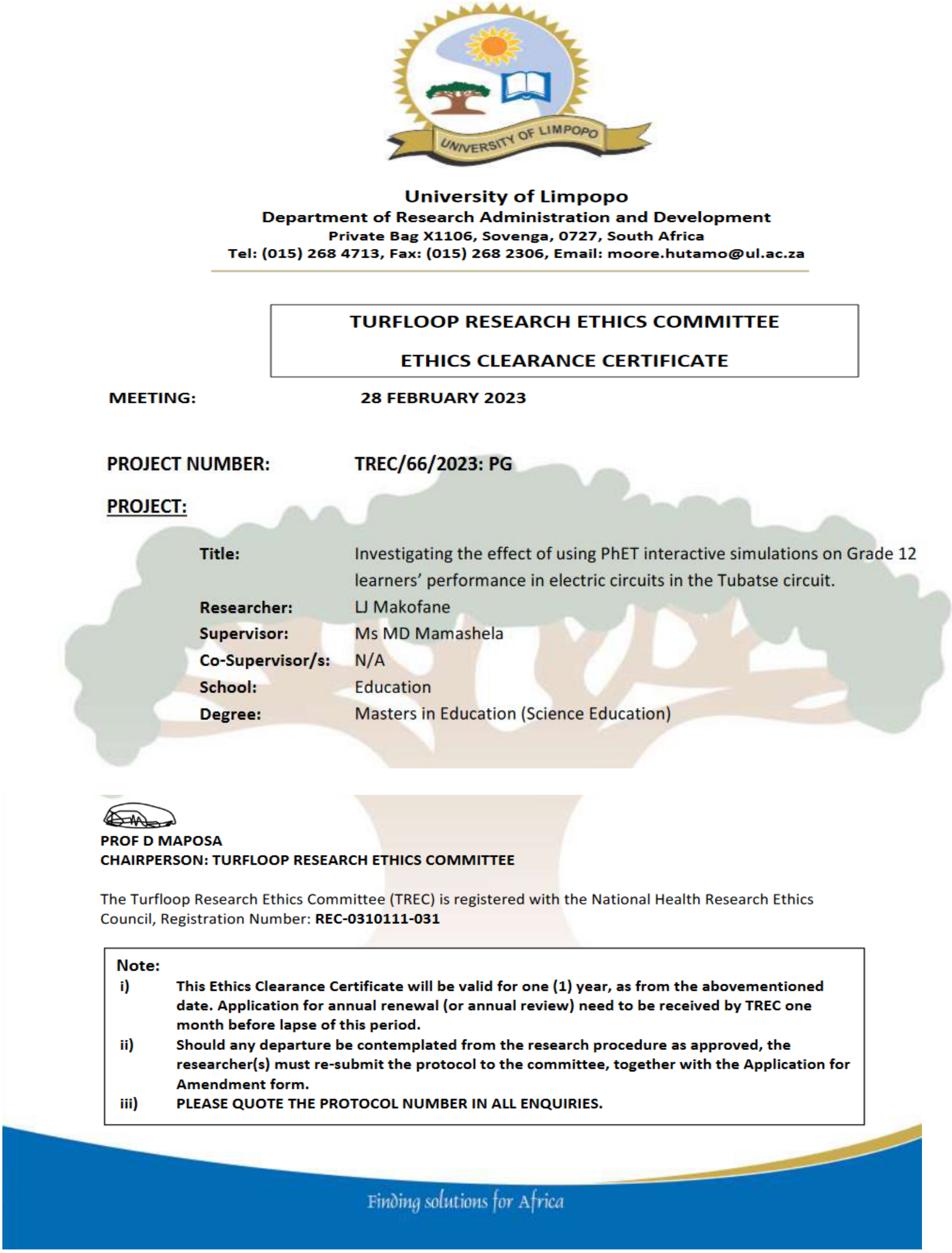
ANNEXURES

ANNEXURE A: Ethical Clearance Certificate



University of Limpopo
Department of Research Administration and Development
Private Bag X1106, Sovenga, 0727, South Africa
Tel: (015) 268 4713, Fax: (015) 268 2306, Email: moore.hutamo@ul.ac.za

TURFLOOP RESEARCH ETHICS COMMITTEE

ETHICS CLEARANCE CERTIFICATE

MEETING: **28 FEBRUARY 2023**

PROJECT NUMBER: **TREC/66/2023: PG**

PROJECT:

Title:	Investigating the effect of using PhET interactive simulations on Grade 12 learners’ performance in electric circuits in the Tubatse circuit.
Researcher:	LJ Makofane
Supervisor:	Ms MD Mamashela
Co-Supervisor/s:	N/A
School:	Education
Degree:	Masters in Education (Science Education)

PROF D MAPOSA
CHAIRPERSON: TURFLOOP RESEARCH ETHICS COMMITTEE

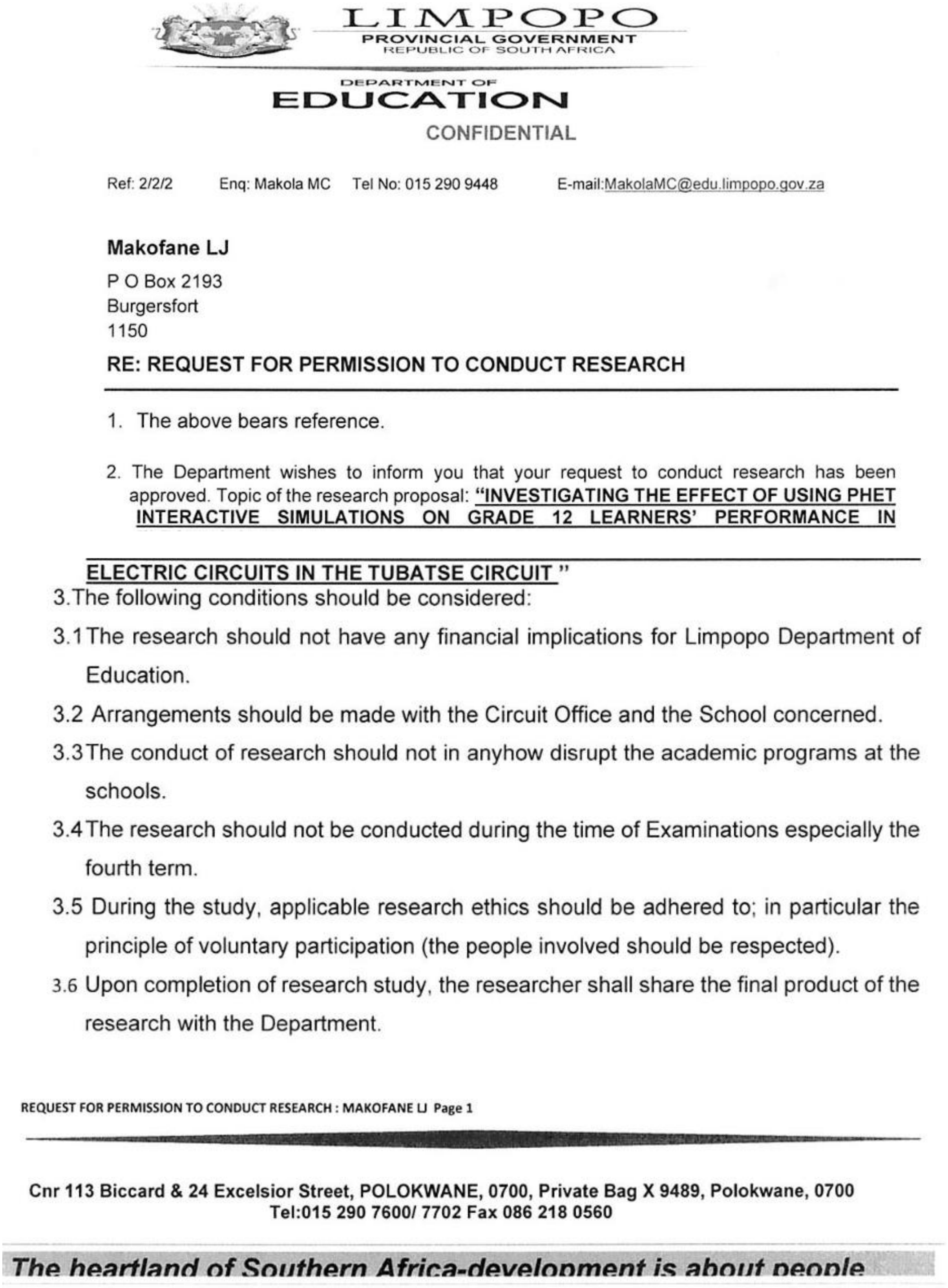
The Turfloop Research Ethics Committee (TREC) is registered with the National Health Research Ethics Council, Registration Number: **REC-0310111-031**

Note:

- **i)** **This Ethics Clearance Certificate will be valid for one (1) year, as from the abovementioned date. Application for annual renewal (or annual review) need to be received by TREC one month before lapse of this period.**
- **ii)** **Should any departure be contemplated from the research procedure as approved, the researcher(s) must re-submit the protocol to the committee, together with the Application for Amendment form.**
- **iii)** **PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES.**

Finding solutions for Africa

ANNEXURE B: Permission from Limpopo Department of Education



LIMPOPO
PROVINCIAL GOVERNMENT
REPUBLIC OF SOUTH AFRICA

DEPARTMENT OF
EDUCATION

CONFIDENTIAL

Ref: 2/2/2 Enq: Makola MC Tel No: 015 290 9448 E-mail:MakolaMC@edu.limpopo.gov.za

Makofane LJ
P O Box 2193
Burgersfort
1150

RE: REQUEST FOR PERMISSION TO CONDUCT RESEARCH

1. The above bears reference.

2. The Department wishes to inform you that your request to conduct research has been approved. Topic of the research proposal: **"INVESTIGATING THE EFFECT OF USING PHET INTERACTIVE SIMULATIONS ON GRADE 12 LEARNERS' PERFORMANCE IN ELECTRIC CIRCUITS IN THE TUBATSE CIRCUIT "**

3. The following conditions should be considered:

3.1 The research should not have any financial implications for Limpopo Department of Education.

3.2 Arrangements should be made with the Circuit Office and the School concerned.

3.3 The conduct of research should not in anyhow disrupt the academic programs at the schools.

3.4 The research should not be conducted during the time of Examinations especially the fourth term.

3.5 During the study, applicable research ethics should be adhered to; in particular the principle of voluntary participation (the people involved should be respected).

3.6 Upon completion of research study, the researcher shall share the final product of the research with the Department.

REQUEST FOR PERMISSION TO CONDUCT RESEARCH : MAKOFANE LJ Page 1

Cnr 113 Biccard & 24 Excelsior Street, POLOKWANE, 0700, Private Bag X 9489, Polokwane, 0700
Tel:015 290 7600/ 7702 Fax 086 218 0560

The heartland of Southern Africa-development is about people

4 Furthermore, you are expected to produce this letter at Schools/ Offices where you intend conducting your research as an evidence that you are permitted to conduct the research.

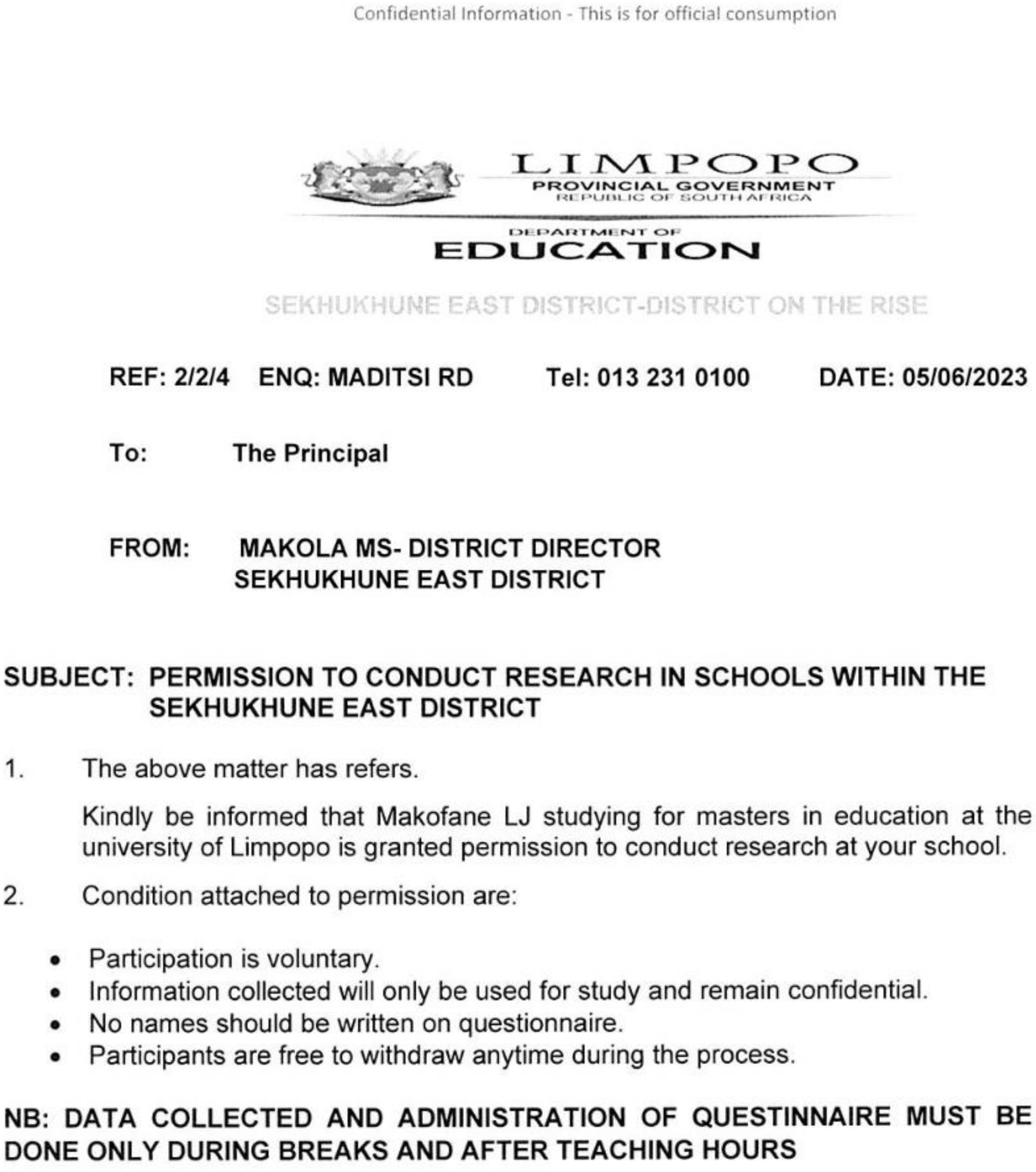
5 The department appreciates the contribution that you wish to make and wishes you success in your investigation.

Best wishes.

Mashaba KM
DDG: CORPORATE SERVICES

13/04/2023
Date

ANNEXURE C: Permission from Sekhukhune East District



Confidential Information - This is for official consumption

LIMPOPO
PROVINCIAL GOVERNMENT
REPUBLIC OF SOUTH AFRICA

DEPARTMENT OF
EDUCATION

SEKHUKHUNE EAST DISTRICT-DISTRICT ON THE RISE

REF: 2/2/4 ENQ: MADITSI RD Tel: 013 231 0100 DATE: 05/06/2023

To: The Principal

FROM: MAKOLA MS- DISTRICT DIRECTOR
SEKHUKHUNE EAST DISTRICT

SUBJECT: PERMISSION TO CONDUCT RESEARCH IN SCHOOLS WITHIN THE SEKHUKHUNE EAST DISTRICT

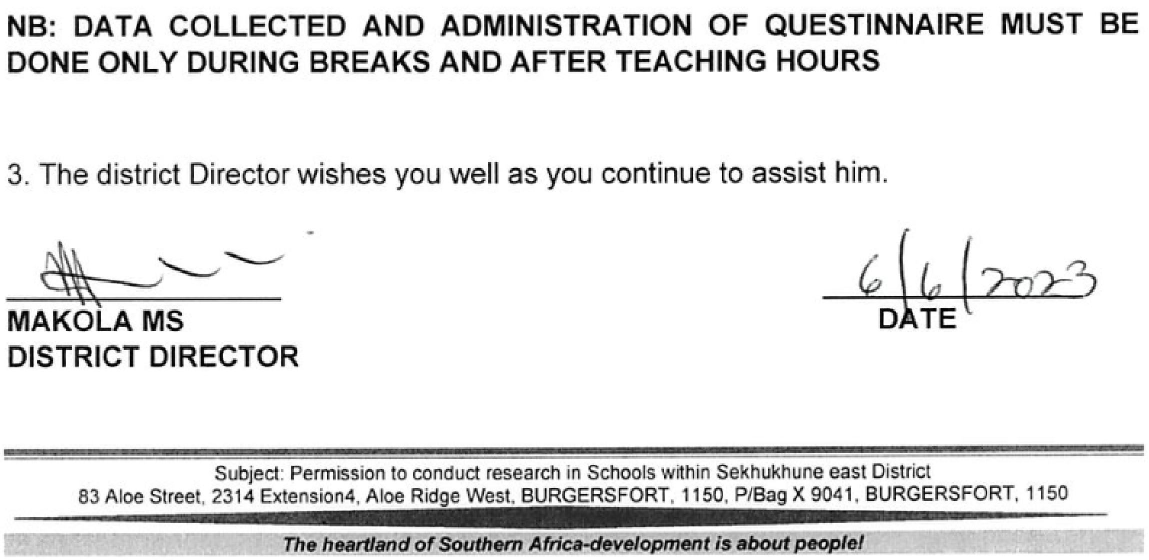
1. The above matter has refers.

   Kindly be informed that Makofane LJ studying for masters in education at the university of Limpopo is granted permission to conduct research at your school.

2. Condition attached to permission are:

- Participation is voluntary.
- Information collected will only be used for study and remain confidential.
- No names should be written on questionnaire.
- Participants are free to withdraw anytime during the process.

NB: DATA COLLECTED AND ADMINISTRATION OF QUESTINNAIRE MUST BE DONE ONLY DURING BREAKS AND AFTER TEACHING HOURS



NB: DATA COLLECTED AND ADMINISTRATION OF QUESTINNAIRE MUST BE DONE ONLY DURING BREAKS AND AFTER TEACHING HOURS

3. The district Director wishes you well as you continue to assist him.

6/6/2023

DATE

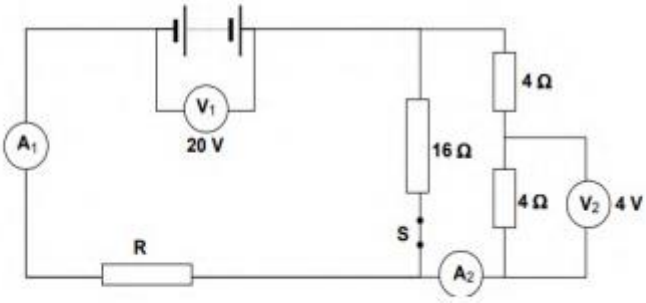
MAKOLA MS
DISTRICT DIRECTOR

ANNEXURE D: INSTRUMENT 1:Pre-test

Marks: 50 **Duration: 60 minutes**

Question 1

In the electric circuit represented below, the battery has **emf of 24 V**. The ammeter and connecting wires have negligible resistance.



When the **Switch S is closed** voltmeter V_1 registers 20 V and V_2 registers 4 V.

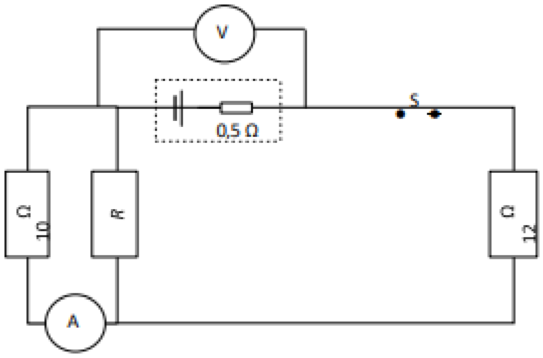
1.1. Calculate:

- 1.1.1. The reading on A_2. (4)
- 1.1.2. The reading on A_1. (4)
- 1.1.3. The resistance of resistor R. (3)
- 1.1.4. The internal resistance of the battery. (3)
- 1.1.5. The energy transferred in resistor R in 10 minutes. (4)

1.2. Switch S is now opened. State whether reading on V_1 will increase, decrease or stay the same: briefly explain your answer. (4)

Question 2

A circuit is connected as shown below. The resistance of R, which is connected in parallel with the 10 Ω resistor, is unknown. With switch S closed, the reading on voltmeter V decreases from 45 V to 43,5 V. The internal resistance of the battery is 0,5 Ω.



2.1. Calculate the reading on ammeter A. Show ALL your calculations. (8)

2.2. Determine the resistance of resistor R. (4)

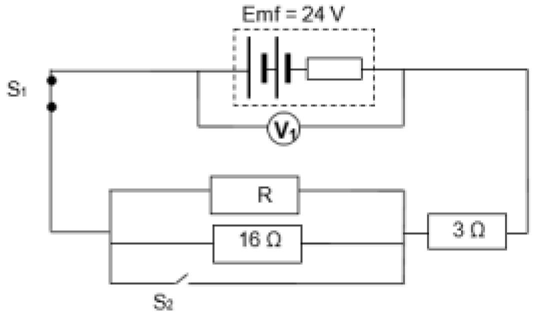
2.3. Resistor R burns out how will each of the following be affected? Write INCREASE, DECREASE OR REMAIN THE SAME.

2.3.1. The reading on the ammeter (1)

2.3.2. The reading on voltmeter V Give a reason for your answer. (4)

QUESTION 3

A circuit is connected as shown below. When switch S1 is closed, $V_{external}$ is equal to 22,5 V. The internal resistance of the battery is 0.8 Ω.



3.1. State Ohm’s law in words. (2)

3.2. Calculate the power dissipated by the 16 Ω resistor. (6)

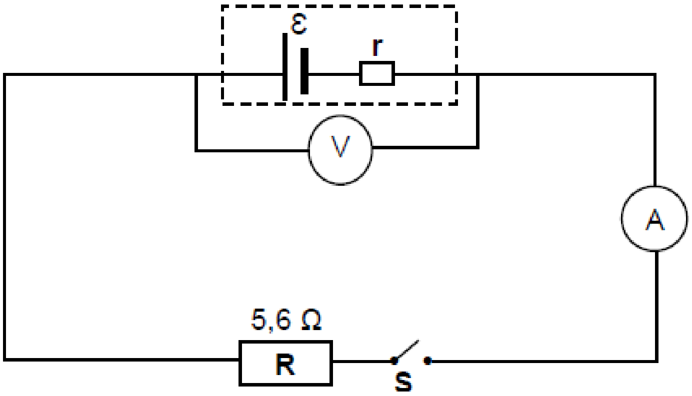
3.3. Calculate the resistance of R. (3)

3.4. Switch S2 is now closed. How will voltmeter reading V1 be influenced?
(Write down only INCREASE, DECREASE or STAYS THE SAME.)
Give an explanation to your answer. (4)

ANNEXURE E: INSTRUMENT 2: Post-test

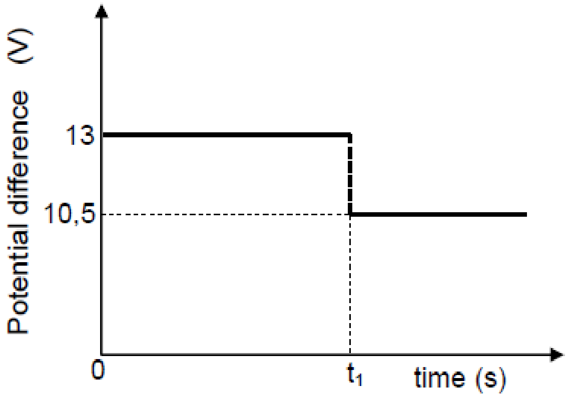
In the circuit diagram below, resistor **R**, with a resistance of 5,6 Ω, is connected, together with a switch, an ammeter and a high-resistance voltmeter, to a battery with an unknown internal resistance, **r**.

The resistance of the connecting wires and the ammeter may be ignored.



The graph below shows the potential difference across the terminals of the battery as a function of time.

At time t_1, switch **S** is closed.



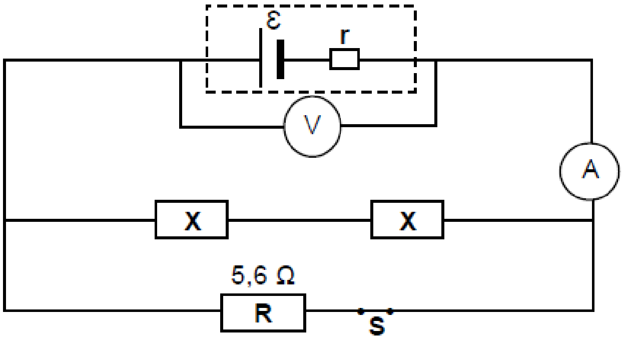
1.1 Define the term *emf* of a battery. (2)

1.2 Write down the value of the emf of the battery. (1)

1.3 When switch **S** is CLOSED, calculate the:

- 1.3.1 Current through resistor **R** (3)
- 1.3.2 Power dissipated in resistor **R** (3)
- 1.3.3 Internal resistance, **r**, of the battery (3)

1.4 Two IDENTICAL resistors, each with resistance **X**, are now connected in the same circuit with switch **S** closed, as shown below.



The ammeter reading now increases to 4 A.

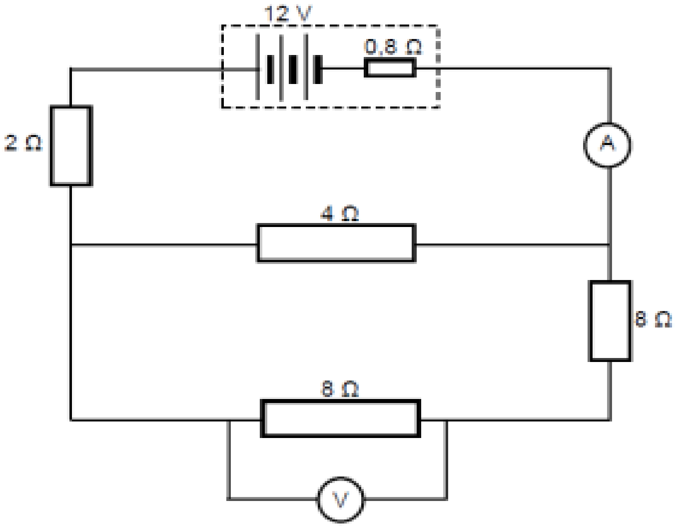
1.4.1 How would the voltmeter reading change? Choose from INCREASES, DECREASES or REMAINS THE SAME.

Give a reason for the answer by referring to $V_{\text{internal resistance}}$. (2)

1.4.2 Calculate resistance **X**. (5)

QUESTION 2

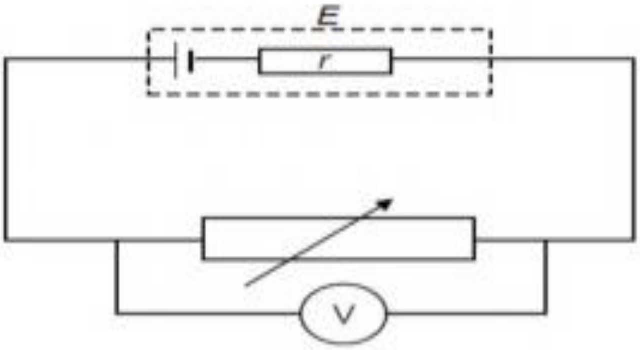
2.2 In the circuit diagram below, the battery has an emf of 12 V and an internal resistance of 0,8 Ω. The resistance of the ammeter and connecting wires may be ignored.



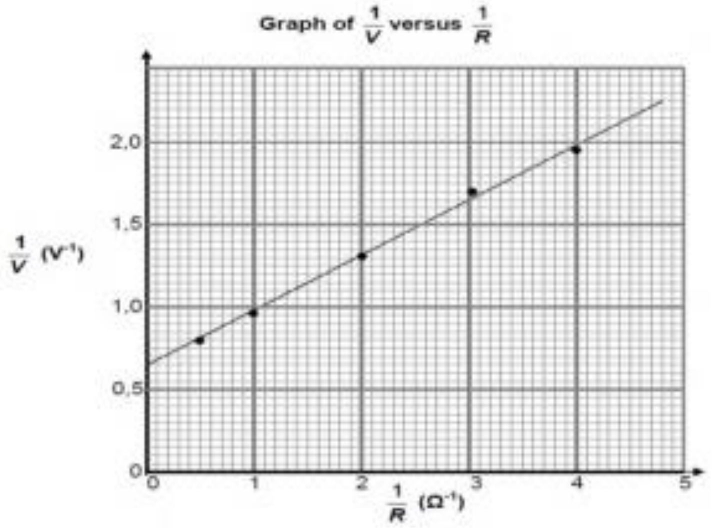
	Calculate the:		
	2.2.1	Effective resistance of the circuit	(4)
	2.2.2	Reading on the ammeter	(3)
	2.2.3	Reading on the voltmeter	(4)
			[13]

QUESTION 3

3.1 In an experiment, learners use the circuit below to determine the internal resistance of a cell.



The circuit consists of a cell of emf E and internal resistance r. A voltmeter is placed across a variable resistor which can be set to known values R. They obtain the graph below.

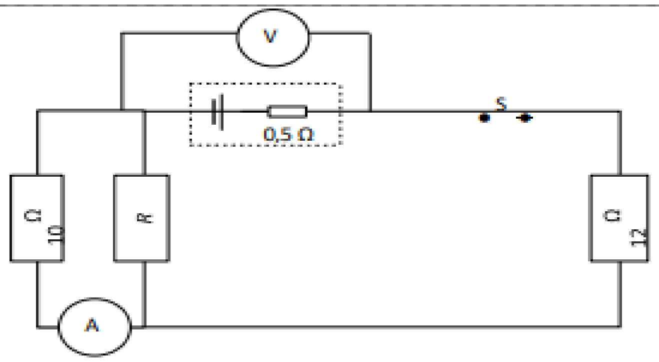


Use the graph to determine the following:

3.1.1	The equation of the graph in the form of y=mx+c	(1)
3.1.2	The mathematical relationship for the slope of the graph	(1)
3.1.3	Emf of the cell	(2)
3.1.4	The internal resistance of the cell	(3)
		[7]

QUESTION 4

A circuit is connected as shown below. The resistance of *R*, which is connected in parallel with the 10 Ω resistor, is unknown. With switch S closed, the reading on voltmeter V decreases from 45 V to 43,5 V. The internal resistance of the battery is 0,5 Ω.



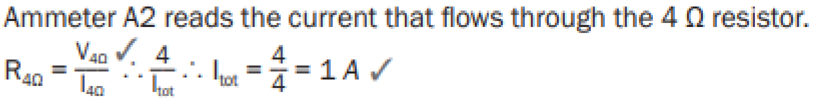
4.1 Calculate the reading on ammeter A. Show ALL your calculations. (8)

4.2 Determine the resistance of resistor *R*. (3)

Resistor R burns out how will each of the following be affected? Write **INCREASE, DECREASE OR REMAIN THE SAME**

ANNEXURE F: MARKING GUIDELINES FOR INSTRUMENT 1: Pre-test

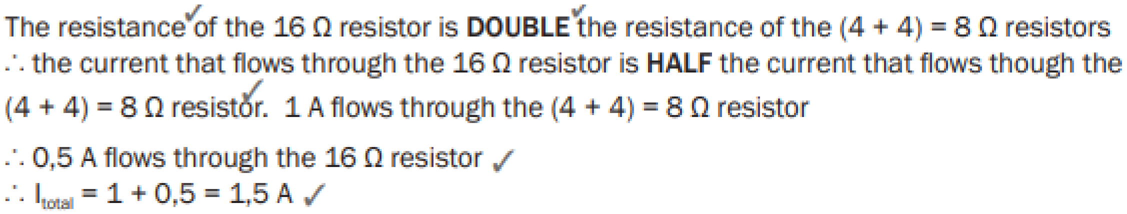
1.1.1.



Ammeter A2 reads the current that flows through the 4 Ω resistor.

$R_{4\Omega} = \frac{V_{4\Omega}}{I_{4\Omega}}$ ✓ ∴ $\frac{4}{I_{tot}}$ ∴ $I_{tot} = \frac{4}{4} = 1\ A$ ✓

1.1.2.

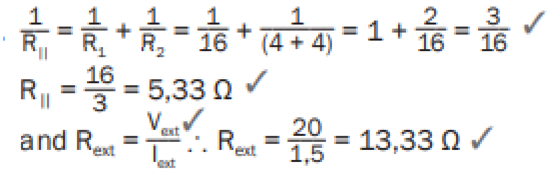


The resistance ✓ of the 16 Ω resistor is **DOUBLE** ✓ the resistance of the (4 + 4) = 8 Ω resistors ∴ the current that flows through the 16 Ω resistor is **HALF** the current that flows though the (4 + 4) = 8 Ω resistor. ✓ 1 A flows through the (4 + 4) = 8 Ω resistor

∴ 0,5 A flows through the 16 Ω resistor ✓

∴ $I_{total} = 1 + 0,5 = 1,5\ A$ ✓

1.1.3.

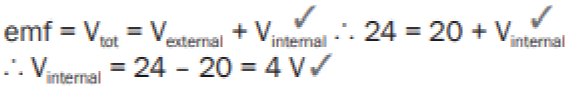


$$\frac{1}{R_{||}} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{16} + \frac{1}{(4+4)} = 1 + \frac{2}{16} = \frac{3}{16}$$ ✓

$R_{||} = \frac{16}{3} = 5,33\ \Omega$ ✓

and $R_{ext} = \frac{V_{ext}}{I_{ext}}$ ✓ ∴ $R_{ext} = \frac{20}{1,5} = 13,33\ \Omega$ ✓

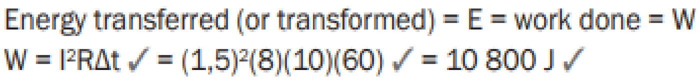
1.1.4.



emf = $V_{tot} = V_{external} + V_{internal}$ ✓ ∴ $24 = 20 + V_{internal}$ ✓

∴ $V_{internal} = 24 - 20 = 4\ V$ ✓

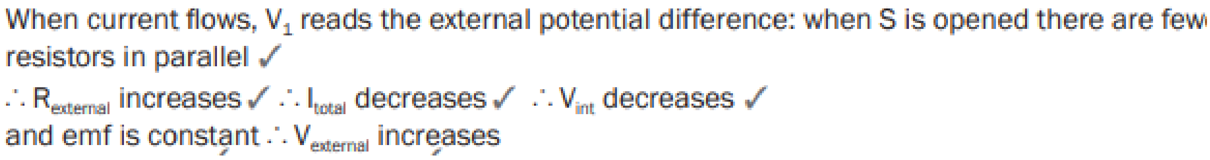
1.1.5.



Energy transferred (or transformed) = E = work done = W

$W = I^2R\Delta t$ ✓ $= (1,5)^2(8)(10)(60)$ ✓ $= 10\ 800\ J$ ✓

1.2



When current flows, V_1 reads the external potential difference: when S is opened there are few resistors in parallel ✓

∴ $R_{external}$ increases ✓ ∴ I_{total} decreases ✓ ∴ V_{int} decreases ✓

and emf is constant ∴ $V_{external}$ increases

Question 2

2.1.

$V_{int} = 45 - 43{,}5 = 1{,}5\ V$ ✓

$I = \frac{V}{R}$ ✓ $= \frac{1{,}5}{0{,}5 ✓} = 3\ A$ OR/OF

emf/*emk* = $V_{ext} + V_{int}$ ✓
$45 = 43{,}5$ ✓ $+ I(0{,}5)$ ✓

$I = 3\ A$

$V_{12\,\Omega} = IR_{12\,\Omega} = 3 \times 12$ ✓ $= 36\ V$ OR/OF

$V_{//} = 43{,}5 \overset{✓}{-} 36 = 7{,}5\ V$ ✓

$I = \frac{V_{//}}{R} = \frac{7{,}5}{10 ✓} = 0{,}75\ A$ ✓

emf/emk = I(R+r) OR/*OF* V = IR
$45 = 3(R + 0{,}5)$ ✓ $45 = 3R$✓
$R = 14{,}5\ \Omega$ $R = 15\ \Omega$

$R_p = 14{,}5 - 12 = 2{,}5\ \Omega$ ✓ $R_p = 15 - 12 - 0{,}5 = 2{,}5\ \Omega$✓

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2}$$

$$\frac{1}{2{,}5} = \frac{1}{10} + \frac{1}{r}$$

$R = 3{,}33\ \Omega$ ✓

Current divides in ratio 3:1

$\frac{1}{4} \times 3$ ✓ $= 0{,}75\ A$✓

[12.1.3] (8)

2.2

$I_R = 3 - 0{,}75 = 2{,}25\ A$ ✓

$R = \frac{V_{//}}{I} = \frac{7{,}5 ✓}{2{,}25} = 3{,}33\ \Omega$ ✓ OR/OF

emf/*emk* = I(R+r)
$45 = 3(R + 0{,}5)$ ✓
$R = 14{,}5\ \Omega$

$R_p = 14{,}5 - 12 = 2{,}5\ \Omega$ ✓

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} \therefore \frac{1}{2{,}5} = \frac{1}{10} + \frac{1}{r} \therefore R = 3{,}33\ \Omega ✓$$

2.3.1 Decreases

2.3.2

Increases/*Toeneem* ✓
The total resistance increases, ✓
therefore the current decreases✓ therefore $V_{internal}$ decrease ✓ therefore reading on V increases
Die totale weerstand neem toe Stroom neem af, V_{intern} *neem af en dus neem V toe*

Question 3

3.1.

The potential difference across a conductor is directly proportional to the current in the conductor✓ at constant temperature.✓		(2)

3.2

OPTION 1 / OPSIE 1

$R = \frac{V}{I}$

$= \frac{21}{3}$ ✓

$= 7\ \Omega$

$R_p = 7 - 3$✓

$= 4\Omega$

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

$\frac{1}{4}$ ✓$= \frac{1}{6} + \frac{1}{R}$ ✓

$\therefore R = 12\ \Omega$

$V_p = 21 - 9$

$= 12\ V$

$P = \frac{V^2}{R}$

$P = \frac{12^2}{12}$ ✓ ✓

$= 12\ W$✓

$E = I(R + r)$

$24 = 3(R + 1)$ ✓

$R = 7\ \Omega$

$R_p = 7 - 3$✓

$= 4\Omega$

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

$\frac{1}{4}$ ✓$= \frac{1}{6} + \frac{1}{R}$ ✓

$\therefore R = 12\ \Omega$

Ratio of current in parallel branches:2:1/*Verhouding van stroom i parallelle vertakking: 2:1*

$I_R = 1\ A$

$P = IR^2$

$= (1)$ ✓ (12) ✓

$= 12\ W$✓

3.4

Increase✓/*vergroot*
Total resistance in circuit decrease.✓/*Totale weerstand in stroombaan verklein.*
Total current increase✓ (and through 3 Ω resistor)./*Totale stroom vegroot*
Therefore: Power increase according to P= I^2R for R (3Ω) staying constant.✓/
Daarom: Drywing vergroot ooreenstemmend met P = I^2R vir R (3 Ω) bly konstant.

ANNEXUER G: MARKING GUIDELINES FOR INSTRUMENT 2: Post-test

QUESTION 1

<u>(Maximum) energy provided (work done)</u> ✓ by a battery per <u>coulomb / unit charge</u> passing through it. ✓
(Maksimum) energie verskaf (arbeid verrig) deur 'n battery per coulomb/eenheidlading wat daardeur beweeg.

ACCEPT/*AANVAAR*:
The reading on a voltmeter connected across a battery when there is no current/ in an open circuit.✓✓
Lesing op 'n voltmeter oor 'n battery as daar geen stroom is nie (2)

1.1.
1.2.

13 V ✓

1.3.1.

$R = \frac{V}{I}$ ✓ $5{,}6 = \frac{10{,}5}{I}$ ✓ $I = 1{,}88$ A ✓ (1,875 A)	**<u>Marking criteria/*Nasienriglyne:*</u>** • Appropriate formula/*Toepaslike formule* ✓ • Whole substitution/*Hele vervanging* ✓ • Final answer/*Finale antwoord*: 1,88 A ✓

1.3.2. POSITVE MARKING FROM 1.3.1

<u>OPTION 1</u>	**<u>OPTION 2</u>**
$P = VI$ ✓ $= (10{,}5)(1{,}88)$ ✓ $= 19{,}74$ W ✓ (19,688 W)	$P = I^2R$ ✓ $= (1{,}88)^2(5{,}6)$ ✓ $= 19{,}79$ W ✓ (19,688 W)
<u>OPTION 3</u> $P = \frac{V^2}{R}$ ✓ $= \frac{10{,}5^2}{5{,}6}$ ✓ $= 19{,}69$ W ✓ (19,688 W)	

1.3.3

<u>OPTION 1/*OPSIE 1*</u>

$\varepsilon = I(R + r)$ ✓

$\underline{13 = 1{,}88\ (5{,}6 + r)}$ ✓

$r = 1{,}31\ \Omega$ ✓ $(1{,}31 – 1{,}33\ \Omega)$

<u>OPTION 2/*OPSIE 2*</u>

$r = \dfrac{V_{internal}}{I}$ ✓

$= \dfrac{2{,}5}{1{,}88}$ ✓

$= 1{,}33\ \Omega$ ✓ $(1{,}31 – 1{,}33\ \Omega)$

<u>OPTION 3/*OPSIE 3*</u>

$\varepsilon = V_{ext} + V_{int}$

$13 = 10{,}5 + V_{int}$

$V_{int} = 2{,}5\ V$

$V_{int} = Ir$ ✓

$2{,}5 = (1{,}88)r$ ✓

$r = 1{,}31\ \Omega$ ✓ $(1{,}31 – 1{,}33\ \Omega)$

1.4.1.

Decreases/*Neem af* ✓

$V_{internal\ resistance}$/Internal volts increase ✓

$V_{interne\ weerstand}$/Interne volts neem toe (2)

1.4.2

<u>OPTION 1/*OPSIE 1*</u>

$\varepsilon = I(R + r)$ ✓

$\underline{13 = 4\ (R_{ext} + 1{,}31)}$ ✓

$R_{ext} = 1{,}94\ \Omega\ \ (1{,}92\ \Omega)$

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{1{,}94} = \frac{1}{5{,}6} + \frac{1}{R_2}\ ✓$$

$R_2 = 2{,}97\ \Omega\ \ (2{,}92\ \Omega)$

$X = \frac{1}{2}(2{,}97)$ ✓

$= 1{,}49\ \Omega$ ✓ $(1{,}46 – 1{,}49\ \Omega)$

<u>OPTION 2/*OPSIE 2*</u>

$\varepsilon = I(R + r)$ ✓

$\underline{13 = 4(R_{ext} + 1{,}31)}$ ✓

$R_{ext} = 1{,}94\ \Omega\ \ (1{,}92\ \Omega)$

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

$$1{,}94 = \frac{5{,}6\ R_2}{5{,}6 + R_2}\ ✓$$

$R_2 = 2{,}97\ \Omega\ (2{,}92\ \Omega)$

$X = \frac{1}{2}(2{,}97)$ ✓

$= 1{,}49\ \Omega$ ✓ $(1{,}46 – 1{,}49\ \Omega)$

<u>OPTION 3/*OPSIE 3*</u>

$\varepsilon = I(R + r)$ ✓

$\underline{13 = 4(R_{ext} + 1{,}31)}$ ✓

$R_{ext} = 1{,}94\ \Omega\ \ (1{,}92\ \Omega)$

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\left[\frac{1}{1{,}94} = \frac{1}{5{,}6} + \frac{1}{2X✓}\right]✓$$

$X = 1{,}49\ \Omega$ ✓ $(1{,}46 – 1{,}49\ \Omega)$

<u>OPTION 4/*OPSIE 4*</u>

$\varepsilon = I(R + r)$ ✓

$\underline{13 = 4(R_{ext} + 1{,}31)}$ ✓

$R_{ext} = 1{,}94\ \Omega\ \ (1{,}92\ \Omega)$

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

$$\left[1{,}94 = \frac{(5{,}6)(2X)}{5{,}6 + 2X✓}\right]✓$$

$X = 1{,}49\ \Omega$ ✓

QUESTION 2

2.2.1

$$\frac{1}{R}=\frac{1}{r_1}+\frac{1}{r_2}\ \checkmark=\frac{1}{4}+\frac{1}{16}\ \checkmark$$

$\therefore R = 3{,}2\ \Omega$

$R_{\text{effective/}\textit{effektief}} = 3{,}2\ \Omega + 2\ \Omega + 0{,}8\ \Omega\ \checkmark$

$= 6\ \Omega\ \checkmark$

2.2.2

Option 1/*Opsie 1*:	**Option 2/*Opsie 2*:**
$V = IR$ ✓ $12 = I(6)$ ✓ $I = 2\ \text{A}$ ✓	$\text{emf} = I(R + r)$ ✓ $12 = I(5{,}2 + 0{,}8)$ ✓ $I = 2\ \text{A}$ ✓

2.2.3

Option 1/*Opsie 1*: $V_{\text{parallel}} = IR$ ✓ $=(2)(3{,}2)$ ✓ $= 6{,}4\ \text{V}$ $V_{8\Omega} = \frac{6{,}4}{2}$ ✓ $= 3{,}2\ \text{V}$ ✓	**Option 2/*Opsie 2*:** $Vp = \frac{R_p}{R} \times V$ ✓ $= \frac{3{,}2}{6}$ ✓ $\times 12$ ✓ $= 6{,}4\ \text{V}$ $\therefore V_{8\Omega} = 3{,}2\ \text{V}$ ✓
Option 3/*Opsie 3*: $I_{8\Omega} = \frac{4}{20}(2)$ ✓ $= 0{,}4\ \text{A}$ $V_{8\Omega} = IR$ ✓ $= (0{,}4)(8)$ ✓ $= 3{,}2\ \text{V}$ ✓	**Option 4/*Opsie 4*:** $\text{emf} = I(R + r)$ ✓ $12 = IR_{2\ \Omega} + V_p + Ir$ $12 = (2)(2) + V_p + (2)(0{,}8)$ ✓ $Vp = 6{,}4\ \text{V}$ $V_{8\Omega} = \frac{6{,}4}{2}$ ✓ $= 3{,}2\ \text{V}$ ✓

QUESTION 3

3.1.1.

$$\frac{1}{V}=\frac{r}{ER}+\frac{1}{E}$$

3.1.2

From graph/*Van grafiek*: $\frac{R}{V}$ ✓

OR/*OF*

From equation/*Van vergelyking*: $\frac{r}{E}$ (1)

3.1.3

$\frac{1}{E} = 0,65$ ✓

$\therefore E = 1,54$ V✓ (2)

3.1.4

$\frac{r}{E} = \frac{2 - 1✓}{4 - 1✓}$

$\therefore r = 0,51\ \Omega$ ✓

(Any set of values from the graph can be used to calculate the gradient./*Enige stel waardes van die grafiek kan gebruik word om die gradiënt te bereken.)* (3)