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A Study on the Impact of Physics Education Technology (Phet) Simulations on Physics Education in Zambian Secondary Schools

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Abstract- This mixed-methods quasi-experimental study evaluated the impact of Physics Education Technology (PhET) interactive simulations on Grade 11 students' conceptual understanding and engagement in Zambian secondary schools, addressing a critical gap in STEM education within resource-constrained environments characterized by high student-to-teacher ratios and limited laboratory infrastructure. Conducted over four weeks across four government secondary schools— Nelson Mandela and Kafue Day (urban), and Feira and Nyangwena Combined (rural)—the study involved 120 students and 8 physics teachers using a pre-test/post-test non-equivalent control group design. The experimental group (n=60), taught via PhET simulations integrated through a Predict-Observe-Explain (POE) framework, achieved a post-test mean score of 78.5%, significantly outperforming the control group's 59.8% with a remarkably large Cohen's d effect size of 1.76 ($p < 0.001$). Qualitative data from interviews and observations revealed that simulations made "invisible" concepts like electron flow and magnetic flux visible, while teachers demonstrated "Contextual TPACK" by successfully navigating technical barriers such as a 1:15 laptop-to-student ratio and national load-shedding through offline deployment and collaborative "Inquiry Circles." The study further revealed that rural students achieved nearly identical learning gains to their urban counterparts (+43.8% vs +44.5%), suggesting that PhET simulations act as a "great equalizer" in contexts where physical laboratories are absent. Thematic analysis of teacher interviews identified three key adaptation strategies: resource resilience through collaborative learning, technical agency through offline repositories, and a fundamental pedagogical shift from "lecturer" to "facilitator." The study concludes that PhET simulations, when embedded within a structured inquiry framework, are a powerful, cost-effective tool for bridging the gap between abstract theory and practical understanding in developing world classrooms. Recommendations include the national scale-up of offline digital repositories, integration of simulation-based inquiry into the national syllabus, specialized teacher training in Contextual TPACK, and revision of examination formats to assess conceptual application rather than factual recall. This research contributes empirical evidence to the limited body of literature on ICT integration in Sub-Saharan African secondary education and provides a replicable model for technology-enhanced science instruction in resource-constrained settings.

Keywords- PhET Simulations, Zambia, Mixed-Methods, Cohen's d, TPACK, POE Framework, Contextual TPACK, Load-shedding, STEM Education, Sub-Saharan Africa

I. Introduction

Preamble

My journey as a physics educator in Zambia has been shaped by a persistent paradox: the beauty of physics lies in its ability to explain the fundamental laws of the universe, yet for many Zambian students, it remains an abstract, intimidating, and largely "invisible" subject. Growing up in a school system where a single tattered textbook often served an entire classroom, I experienced firsthand the struggle of trying to visualize magnetic flux or electron flow from static, two- dimensional chalk drawings. This study is born out of the conviction that the "digital divide" should not be a barrier to conceptual clarity. It explores how PhET (Physics Education Technology) simulations can transform the Zambian classroom from a space of rote memorization into a dynamic laboratory of inquiry, even when physical equipment is scarce and power is unreliable.

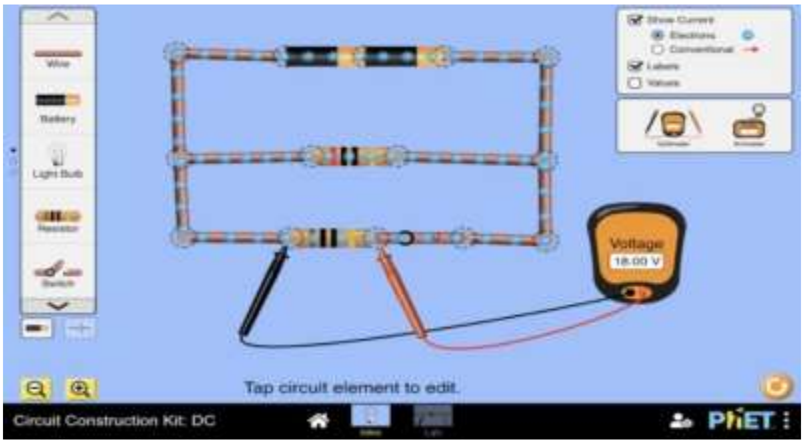
Background of the Study

In the contemporary global landscape, Science, Technology, Engineering, and Mathematics (STEM) education is recognized as the engine of national development. For Zambia, a nation striving to industrialize and diversify its economy under the 8th National Development Plan (2022–2026), physics education is critical. However, the Zambian secondary school sector faces systemic challenges. National examination results consistently show that only 35–45% of Grade 12 candidates achieve a "Credit" or better in Science (Physics/Chemistry), with examiners frequently citing "poor conceptual understanding of abstract topics" as a primary cause.

Traditional pedagogy in Zambia remains largely teacher-centered, often referred to as "chalk-and- talk." While the Ministry of Education has advocated for learner-centered approaches, the reality of overcrowded classrooms—sometimes exceeding 60 students—and a chronic shortage of laboratory apparatus makes practical, hands-on learning difficult to implement. Mubita (2021) highlights that this method remains dominant because teachers often lack the resources or the training to implement student-centered inquiry. Furthermore, Mtika and Gates (2010) observe that the pressure of a centralized curriculum often forces teachers to prioritize syllabus coverage over conceptual depth, a problem that Ertmer (1999) identifies as a "second-order barrier"—the internal beliefs and attitudes of teachers toward pedagogical change.

Interactive simulations like PhET offer a bridge across these barriers. Research by Finkelstein et al. (2005) demonstrated that students using simulations can actually outperform those using real laboratory equipment because simulations allow for the visualization of abstract concepts—such as electron flow or magnetic fields—that are invisible in a traditional lab. Similarly, Hennessy et al. (2010) emphasize that the use of simulations in resource-constrained schools can "level the playing field," providing high-quality scientific experiences to students who lack access to physical laboratories.

Figure 1.1: Sample of PhET Interactive Simulation Interface (Circuit Construction Kit)



Tap circuit element to edit.

Source: PhET Interactive Simulations, University of Colorado Boulder

Statement of the Problem

Despite the theoretical benefits of ICT, there is a significant lack of empirical evidence regarding the effectiveness of PhET simulations in Zambian government schools. While international studies suggest that simulations improve learning, it is unclear how these tools perform in classrooms with a 1:15 laptop-to-student ratio or during periods of national load-shedding.

The core of the problem lies in the disconnect between digital potential and classroom reality. While Gambari et al. (2016) found significant academic gains using simulations in other African contexts, there is a scarcity of data regarding the "Contextual TPACK" (Technological Pedagogical Content Knowledge) required by Zambian teachers. As Kanyadago (2018) suggests, technology alone is not a "silver bullet"; its success depends on how it is mediated by the teacher within specific constraints. This study addresses the gap identified by Probyn (2015), who points out that many ICT interventions fail because they do not account for the linguistic and resource- based complexities of the African science classroom. Without local evidence, the adoption of digital simulations remains sporadic and unsupported by policy-level data.

Purpose of the Study

The primary purpose of this study is to evaluate the impact of PhET interactive simulations on Grade 11 students' academic achievement and engagement in physics, and to explore the lived experiences of teachers integrating these tools in resource-constrained Zambian secondary schools.

Research Objectives

1. To evaluate academic performance: Compare the post-test scores of students taught using PhET simulations versus those taught using traditional methods.
2. To assess student engagement: Examine the levels of cognitive, emotional, and behavioral engagement among students using PhET simulations.
3. To explore teacher adaptation: Identify the pedagogical strategies (Contextual TPACK) and challenges experienced by teachers during the integration of digital simulations in under-resourced schools.

Research Questions and Hypotheses Research Questions

RQ1: Is there a significant difference in post-test scores between students taught through PhET- enhanced inquiry and those taught through traditional lecture methods?
RQ2: How do PhET simulations influence student engagement during physics lessons in urban vs. rural settings?
RQ3: How do teachers navigate the technical and environmental barriers (e.g., load-shedding) to implement simulation-based learning?

Hypotheses

H_0 (Null): There is no significant difference in the mean scores of students taught with PhET simulations and those taught with traditional methods.
H_1 (Alternative): Students taught with PhET simulations will achieve significantly higher mean scores than those taught with traditional methods, as measured by the Physics Conceptual Understanding Test (PCUT).

Significance of the Study

This research is significant at several levels

For Teachers: It provides a proven pedagogical framework for using technology in low-resource settings, offering strategies to handle high student-to-device ratios.
For Policymakers: It offers empirical evidence for the Ministry of Education to support the distribution of offline digital repositories rather than focusing solely on expensive internet infrastructure.

For Students: It bridges the gap between abstract theory and real-world application, potentially increasing interest in STEM careers.

For the Academy: It adds to the limited body of literature concerning ICT integration in Sub- Saharan African secondary education.

Economic Implications for Zambia

Improving physics education aligns with the national goal of creating a "Smart Zambia." According to the National Policy on ICT in Education (2023), digital literacy is no longer an optional skill but a requirement for the modern workforce. By improving conceptual understanding in physics, the nation can produce better-qualified engineers and technicians who are essential for the mining and renewable energy sectors—the backbone of Zambia's economy.

Table 1.1: Alignment of Study Objectives with Zambia's 8th National Development Plan (8NDP)

Study Objective	8NDP Pillar Alignment	Expected Outcome
Improve Academic Performance in Physics	Human Capital Development	Increased STEM graduation rates
Enhance Teacher Adaptation to New Teaching Methods	Digital Transformation	Enhanced Teacher ICT Competency
Boost Student Engagement through Technology	Innovation and Technology	Increased interest in technical careers

Scope and Delimitations

The study was conducted in four government secondary schools in Lusaka Province. Two schools (Nelson Mandela and Kafue Day) represent urban contexts, while two (Feira and Nyangwena Combined) represent rural contexts. The research focused specifically on Grade 11 students because this level introduces the most abstract concepts in the syllabus, including Electricity, Magnetism, and Thermal Physics. The study was limited to a four-week intervention period, which measures immediate conceptual gains but does not address long-term retention.

Operational Definition of Terms

PhET Simulations: Open-source interactive software that simulates physical phenomena through a "game-like" environment, developed by the University of Colorado Boulder.

- **Predict-Observe-Explain (POE):** A three-stage teaching cycle where students first hypothesize an outcome, observe the simulation, and finally reconcile the two.
- **Contextual TPACK:** The specialized knowledge teachers use to integrate technology while specifically accounting for local constraints like lack of power or devices.
- **Load-shedding:** The scheduled disconnection of electricity supply, common in the Zambian context.

- **Inquiry Circles:** Collaborative learning groups formed around available laptops (typically 15 students per device) to facilitate peer learning during simulation activities.

Organization of the Study

This report is organized into six chapters. Chapter One provides the introduction and background. Chapter Two reviews relevant literature on ICT integration, PhET simulations, and the TPACK framework. Chapter Three describes the mixed-methods methodology. Chapter Four presents the results and analysis. Chapter Five discusses the findings in relation to existing literature. Chapter Six offers conclusions and recommendations for policy and practice.

This report is structured to provide a logical and coherent flow of the research journey. Chapter One has established the background, problem statement, purpose, research questions, and significance of the study, setting the stage for the inquiry into PhET simulations in Zambian secondary schools.

Chapter Two presents a comprehensive review of relevant literature, examining the theoretical frameworks of constructivism and TPACK, the evolution of ICT in African education, empirical studies on PhET simulations, barriers to technology integration in Sub-Saharan Africa, and the Predict-Observe-Explain (POE) pedagogy. The chapter concludes with a synthesis of research gaps and presents the conceptual framework guiding this study.

Chapter Three delineates the research methodology, including the mixed-methods quasi- experimental design, selection of research sites, sampling procedures, the PhET-POE instructional intervention, research instruments, data collection procedures, and ethical considerations. The chapter also describes the pilot study and reliability testing of instruments.

Chapter Four presents the results and analysis of the study, beginning with quantitative findings on academic achievement, including pre-test parity analysis, post-test comparisons, and effect size calculations. The chapter then presents qualitative findings on student engagement and the emergence of Contextual TPACK among teachers, followed by the rural-urban parity analysis and specific conceptual shifts observed during the intervention.

Chapter Five provides a critical discussion of the findings, interpreting the remarkably large effect size, the role of visualization in conceptual understanding, the power of the POE framework, and the development of Contextual TPACK. The chapter also compares the findings with regional studies and discusses the limitations of the research.

Chapter Six concludes the study with a summary of key findings, answers to the research questions, and recommendations for policy, practice, and further research. The chapter presents an implementation roadmap for scaling PhET integration across

Zambia and offers final reflections on the transformative potential of digital simulations in resource-constrained educational contexts.

The References section provides a complete list of all sources cited throughout the report, formatted according to APA 7th edition guidelines.
The Appendices contain all supplementary materials, including research instruments, consent forms, interview guides, observation protocols, lesson plans, and supporting documentation.

II. Literature Review

Introduction

This chapter provides an extensive critical examination of the scholarly literature pertaining to the integration of interactive simulations in physics education, with a particular focus on the PhET (Physics Education Technology) project within the sub-Saharan African context. The review is structured to explore the theoretical foundations of digital learning, the evolution of ICT policies in Zambia, and the empirical evidence regarding conceptual change and student engagement. By synthesizing global research with localized studies, this chapter identifies the critical gaps that necessitate this inquiry into resource-constrained secondary schools.

The literature review is organized into ten main sections. Section 2.2 examines the theoretical framework underpinning this study, including constructivism, Vygotsky's Zone of Proximal Development, and the TPACK framework. Section 2.3 traces the evolution of ICT integration in African education, highlighting policy developments and implementation challenges. Section 2.4 reviews empirical studies on PhET simulations and their impact on conceptual understanding. Section 2.5 focuses specifically on the Zambian physics curriculum and the role of ICT.

Section 2.6 analyzes barriers to digital integration in Sub-Saharan Africa, distinguishing between first- order and second-order barriers. Section 2.7 explores student engagement and achievement emotions in technology-enhanced learning. Section 2.8 examines the Predict-Observe-Explain (POE) pedagogy as an instructional framework for simulations. Section 2.9 synthesizes the research gaps identified in the literature. Section 2.10 presents the conceptual framework guiding this study. Section 2.11 provides a summary of the chapter.

Theoretical Framework: Constructivism and TPACK

Constructivist Learning Theory

The pedagogical foundation of this study is rooted in constructivism, a learning theory that posits knowledge is actively constructed by learners rather than passively received from the environment. Honebein (1996) asserts that knowledge is not a commodity to be transferred from teacher to student but is a cognitive construct built through experience and social interaction. In the context of this study, PhET simulations embody this principle by providing an environment where students can manipulate variables and test hypotheses in real-time, constructing their own understanding of physical phenomena.

Piaget's (1970) cognitive constructivism emphasizes that learners build mental structures through processes of assimilation and accommodation. When students interact with PhET simulations, they encounter phenomena that may conflict with their existing mental models—a state of cognitive dissonance that Piaget termed "disequilibrium." This discomfort motivates learners to accommodate new information, revising their mental models to achieve equilibrium. The Predict-Observe-Explain (POE) framework used in this study is specifically designed to create and leverage this cognitive dissonance for conceptual change.

Vygotsky (1978) introduced the concept of the Zone of Proximal Development (ZPD) which serves as a cornerstone for this study's pedagogical approach. He argues that students learn most effectively when they are supported by "scaffolding"—in this case, the visual cues and interactive feedback provided by the simulation and the teacher's guided inquiry. The ZPD represents the gap between what a learner can do independently and what they can achieve with guidance. PhET simulations, when combined with collaborative "Inquiry Circles" and teacher facilitation, provide the scaffolding necessary for students to operate within their ZPD, gradually developing independent understanding of abstract physics concepts.

Social constructivism, also derived from Vygotsky's work, emphasizes the role of social interaction in learning. The collaborative "Inquiry Circles" necessitated by the 1:15 laptop-to- student ratio in this study actually aligned with social constructivist principles, as students were forced to articulate their thinking, debate predictions, and negotiate meaning with peers. As Vygotsky (1978) famously stated, "What the child can do in cooperation today, he can do alone tomorrow" (p. 87).

The TPACK Framework

Mishra and Koehler (2006) developed the Technological Pedagogical Content Knowledge (TPACK) framework, which is the primary analytical lens used in this research. They argue that effective technology integration is not just about technical skill, but about the complex interplay between three knowledge domains:

- **Content Knowledge (CK):** Knowledge of the subject matter—in this case, physics concepts such as electricity, magnetism, and thermal physics.
- **Pedagogical Knowledge (PK):** Knowledge of teaching methods and practices, including classroom management, lesson planning, and assessment.
- **Technological Knowledge (TK):** Knowledge of technology tools and how to operate them.

The intersections of these domains produce

- Pedagogical Content Knowledge (PCK): Knowledge of how to teach specific content understanding which analogies, examples, and demonstrations work best for teaching particular physics concepts.

- Technological Content Knowledge (TCK): Knowledge of how technology can represent content in new ways for example, how PhET simulations can visualize electron flow in a way that static diagrams cannot.

- Technological Pedagogical Knowledge (TPK): Knowledge of how technology can support teaching practices understanding how to manage a classroom where students are using simulations, or how to design technology-enhanced activities.

Figure 2.1: The TPACK Framework (Mishra & Koehler, 2006)

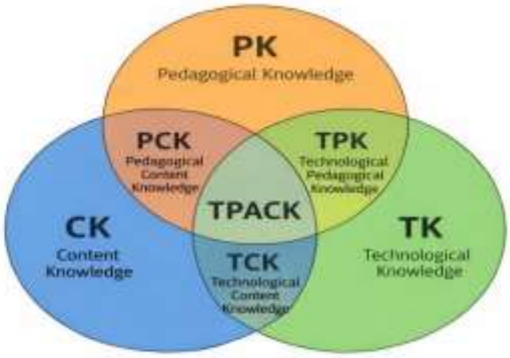


Figure 2.1. *The TPACK Framework (Mishra & Koehler, 2006)*

The central intersection - TPACK - represents the knowledge teachers need to effectively integrate technology, pedagogy, and content in their teaching. However, this study argues that in developing world contexts, a fourth dimension must be considered: Context. This study introduces and operationalizes the concept of "Contextual TPACK" the specialized knowledge teachers use to integrate technology while specifically accounting for local constraints such as load-shedding, limited devices, and lack of internet connectivity. As the findings in Chapter Four reveal, Zambian teachers demonstrated remarkable Contextual TPACK by adapting the POE framework to fit large, under-resourced classrooms through "Inquiry Circles" and offline deployment strategies.

Barriers to Technology Integration

Ertmer (1999) provides a critical distinction between two types of barriers that influence technology integration in education:

- **First-order barriers:** External factors beyond the teacher's control, such as lack of equipment, unreliable electricity, insufficient internet connectivity, and inadequate technical support. These are the infrastructural challenges prevalent in Zambian schools.
- **Second-order barriers:** Internal factors related to teachers' beliefs, attitudes, and pedagogical philosophies. These include resistance to change, lack of confidence with technology, and deeply entrenched traditional teaching practices.

This literature review utilizes Ertmer's framework to analyze why Zambian teachers might struggle with PhET integration even when the software is provided for free. While first-order barriers (load- shedding, limited laptops) are immediately apparent, second-order barriers (beliefs about the teacher's role, skepticism about technology's effectiveness) may be equally significant. The professional development workshops conducted prior to this intervention specifically targeted second-order barriers by demonstrating the pedagogical value of simulations and building teachers' confidence in the POE framework.

Cognitive Theory of Multimedia Learning

Mayer's (2001) Cognitive Theory of Multimedia Learning provides additional theoretical support for the effectiveness of PhET simulations. Mayer proposes that humans process information through two separate channels—visual and auditory—and that learning is enhanced when information is presented through both channels simultaneously. The theory is based on three assumptions:

1. **Dual-channel assumption:** Humans have separate information processing channels for visual and auditory material.
2. **Limited capacity assumption:** Each channel has limited capacity for processing information at any given time.
3. **Active processing assumption:** Meaningful learning occurs when learners engage in cognitive processes including selecting relevant information, organizing it into coherent mental representations, and integrating it with prior knowledge.

PhET simulations align with Mayer's principles by presenting physics concepts through dynamic visual representations (electron flow, field lines, particle motion) accompanied by textual or verbal explanations. This dual-channel presentation reduces extraneous cognitive load—the mental effort required to process information that does not contribute to learning—allowing students to focus their cognitive resources on deeper understanding. In traditional Zambian classrooms, students must exert significant extraneous cognitive load trying to translate a teacher's verbal description of a circuit into a mental image. PhET simulations offload this visualization task, freeing cognitive capacity for higher-order thinking.

The Evolution of ICT in African Education

Historical Overview

Isaacs (2007) provides a comprehensive historical overview of ICT in African education, noting that many nations, including Zambia, initially viewed computers as a subject to be learned (Computer Studies) rather than a tool for learning other subjects like Science. This "computer as curriculum" approach dominated the 1990s and early 2000s, with schools establishing computer laboratories primarily to teach basic computer literacy skills rather than integrating technology across subjects.

Early initiatives were often donor-driven and unsustainable. Isaacs (2007) documents numerous cases where international donors provided computer equipment to African schools without adequate planning for maintenance, teacher training, or curriculum integration. Once external funding ceased and equipment began to fail, these initiatives collapsed, leaving schools with "computer graveyards"—rooms filled with non-functional equipment. This history has created skepticism among some African educators about the long-term viability of technology interventions.

Farrell (2007) specifically examines the Zambian landscape, noting that while the government has made strides in policy development, the "digital divide" remains a stark reality between urban centers like Lusaka and rural outposts. He observes that urban schools may have computer laboratories with internet connectivity, while rural schools often lack electricity entirely. This urban-rural disparity was a key consideration in the selection of research sites for this study, ensuring representation of both contexts.

Policy Developments in Zambia

The Zambian government has recognized the importance of ICT in education through several policy initiatives. The National ICT Policy (2006) identified education as a priority sector for technology integration, calling for the use of ICT to improve access to and quality of education. The National Policy on ICT in Education (2023) represents the most recent policy framework, emphasizing digital literacy as a requirement for the modern workforce and calling for the integration of ICT across all subjects.

Despite these policy developments, implementation has been inconsistent. Mubita (2021) observes that while policies advocate for learner-centered, technology-enhanced instruction, the reality in most Zambian classrooms remains teacher-centered and resource-poor. This policy-practice gap reflects the challenges of translating national vision into classroom reality, particularly in the absence of sustained investment in infrastructure and teacher development.

Unwin (2009) critiques the "one-size-fits-all" approach to digital education in the Global South. He argues that for technology to be meaningful in developing regions, it must be adapted to local realities, such as limited hardware and unreliable power. His work supports the necessity of the "offline" deployment strategy used in this study, which prioritized offline PhET installers and battery-powered devices over internet-dependent solutions.

Regional Perspectives on ICT Integration

Hennessy, Harrison, and Wamakote (2010) conducted a comprehensive review of teacher factors influencing classroom use of ICT in Sub-Saharan Africa. They identified several key findings:

- Teachers' confidence with technology is a critical predictor of integration. Many African teachers have limited personal experience with computers, leading to anxiety about using them in the classroom.
- Pedagogical beliefs significantly influence technology use. Teachers who view their role as transmitting knowledge are less likely to adopt student-centered technology activities than those who see themselves as facilitators of learning.
- Professional development is most effective when it is continuous, school-based, and focused on subject-specific integration rather than generic computer skills.

- Collaborative learning among teachers—communities of practice—can support sustained technology integration.

These findings informed the teacher preparation component of this study, which included a three- day intensive workshop focused on both technical skills (using PhET simulations) and pedagogical strategies (the POE framework). The workshop also established a peer support network among participating teachers, enabling ongoing collaboration throughout the intervention.

PhET Simulations and Conceptual Understanding

The PhET Project

The PhET Interactive Simulations project, founded by Nobel Laureate Carl Wieman at the University of Colorado Boulder, has developed over 150 free interactive simulations for science and mathematics education since its inception in 2002. Wieman et al. (2008) explain that the simulations are designed based on research into how people learn, incorporating features that promote engagement and conceptual understanding:

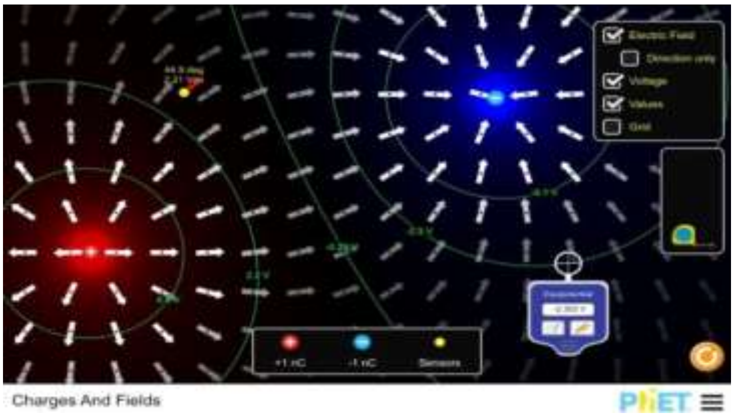
- **Interactive engagement:** Students learn by doing, manipulating variables and observing outcomes.
- **Immediate feedback:** The simulations respond instantly to student actions, providing clear causal relationships.
- **Visual representations:** Abstract concepts are represented visually, making the invisible visible.
- **Game-like environment:** The playful, exploratory nature reduces anxiety and encourages experimentation.
- **Connection to real world:** Simulations connect abstract concepts to real-world phenomena and applications.

Empirical Evidence on PhET Effectiveness

Finkelstein et al. (2005) conducted a landmark study at the University of Colorado which found that students who used PhET simulations to learn about DC circuits performed better on a conceptual survey than those who trained with actual physical equipment. They argue that the simulations' ability to show "invisible" components (like moving electrons) reduces cognitive load and promotes deeper understanding. The study also found that students using simulations demonstrated greater ability to apply their knowledge to novel situations, suggesting that the conceptual understanding gained was more flexible and transferable.

Wieman et al. (2008) emphasize that the simulations are not simply animations but interactive environments that require active engagement. They note that the "game-like" nature of the tools encourages exploration and reduces the fear of making mistakes, which is a common barrier in traditional Zambian science classrooms where students may be hesitant to handle expensive or fragile equipment.

Figure 2.2: Visualization of "Invisible" Phenomena in PhET (Electric Field Lines)



Source: PhET Interactive Simulations, University of Colorado Boulder

Simulations in African Contexts

Hennessy et al. (2010) explored the use of simulations in sub-Saharan African classrooms and found that they significantly improved teacher-student dialogue. They noted that instead of the teacher providing all the answers, the simulation became a shared "third party" that both teacher and student could interrogate. This shift in classroom discourse—from teacher monologue to collaborative inquiry—was identified as a key benefit of simulation use in resource-constrained settings.

Gambari, Kawu, and Falode (2016) conducted a study in Nigeria examining the impact of virtual laboratories on secondary school students' achievement in physics. Using a quasi-experimental design with 120 students, they found that students taught with virtual laboratories achieved significantly higher post-test scores than those taught with traditional methods, with an effect size of $d = 0.82$. The study also found that virtual laboratories were particularly effective for female students, helping to bridge the gender gap in physics achievement.

Banda and Nzabahimana (2023) conducted a study in Rwanda investigating the impact of PhET simulations on students' motivation and academic achievement. Using a mixed-methods design with 240 students across six schools, they found significant gains in both achievement ($d = 0.94$) and motivation. However, they noted that their study did not specifically address the rural-urban divide or the specific technical adaptations required for "off-grid" schools—gaps that this study addresses.

Addressing Misconceptions in Physics

Zacharia (2007) investigated the effectiveness of combining real and virtual experimentation in enhancing students' conceptual understanding of electric circuits. He found that simulations were particularly effective at addressing deeply held misconceptions that persisted despite traditional instruction. The ability to manipulate variables and observe immediate outcomes allowed students to test their mental models against the behavior of the simulation, creating cognitive conflict that led to conceptual change.

This finding is particularly relevant to the Zambian context, where examiners consistently cite "poor conceptual understanding of abstract topics" as a primary cause of low achievement. Topics such as current electricity and electromagnetism are particularly problematic because they involve entities (electrons, magnetic fields) that cannot be directly observed. PhET simulations make these entities visible, providing the empirical evidence needed to challenge and revise misconceptions.

ICT in the Zambian Physics Curriculum

Curriculum Structure and Challenges

The Zambian physics curriculum for Grades 10-12 is content-heavy and examination-oriented. Mubita (2021) observes that this creates a "culture of memorization" where students learn to pass the exam without understanding the underlying physical laws. His research advocates for the integration of digital tools to break this cycle and promote deeper conceptual understanding.

The syllabus includes several topics that are particularly challenging for students:

- **Electricity and Magnetism:** Current, voltage, resistance, series and parallel circuits, electromagnetic induction
- **Thermal Physics:** Heat transfer, gas laws, states of matter
- **Waves and Optics:** Reflection, refraction, wave properties.
- **Modern Physics:** Atomic structure, radioactivity

These topics share a common characteristic: they involve abstract entities and processes that cannot be directly observed. This "invisibility" creates significant barriers to understanding, as students must rely on verbal explanations and static diagrams to construct mental models of phenomena they have never experienced.

The Laboratory Crisis

Haambokoma (2007) identifies that the lack of laboratory facilities in Zambian schools is a primary cause of poor performance in science. He notes that many schools conduct "alternative to practical" exams because they have no equipment, which he describes as a "pedagogical tragedy." Students are expected to answer questions about experiments they have never performed, manipulating equipment they have never seen, observing phenomena they have never experienced.

This study positions PhET simulations as a direct solution to this crisis. While building physical laboratories in every school remains a long-term economic challenge, virtual laboratories offer an immediate, scalable alternative. A single laptop loaded with PhET simulations can provide hundreds of students with interactive, visual experiences of scientific phenomena—experiences that would otherwise be impossible.

Teacher Preparation and Professional Development

The quality of physics teaching in Zambian secondary schools is highly variable. Many physics teachers are teaching out of field, having specialized in other science subjects during their own education. Even those with physics qualifications may lack training in modern pedagogical approaches or technology integration.

Kanyadago (2018) argues that teacher preparation programs must evolve to include training in technology-enhanced pedagogy. He emphasizes that simply providing equipment is insufficient; teachers need sustained professional development that builds both technical skills and pedagogical confidence. This study's teacher training component addressed this need by providing intensive, context-specific preparation in both PhET technical skills and the POE pedagogical framework.

Barriers to Digital Integration in Sub-Saharan Africa

First-Order Barriers: Infrastructure and Resources

Bingimlas (2009) provides a synthesis of barriers to ICT integration, identifying time, training, and resources as the "holy trinity" of obstacles. In the Zambian context, these barriers take specific forms:

- **Infrastructure deficits:** Unreliable electricity supply (load-shedding), lack of internet connectivity, inadequate computer facilities.
- **Equipment shortages:** High student-to-computer ratios (often exceeding 50:1), lack of maintenance and technical support.
- **Resource limitations:** Insufficient budget for technology acquisition and maintenance, lack of appropriate software.

Kanyadago (2018) specifically addresses the "power problem" in East and Central Africa. He argues that reliance on the national grid is a major deterrent for teachers, who cannot plan lessons that depend on technology when power outages are unpredictable. His findings support the "load- shedding" definition used in this study, where teachers must rely on battery-powered laptops and pre-loaded offline simulations. The current study explicitly addresses this barrier by using offline PhET installers and ensuring devices were fully charged before lessons.

Second-Order Barriers: Teacher Beliefs and Attitudes

Ertmer (1999) argues that first-order barriers, while significant, are often easier to address than second-order barriers—the internal beliefs and attitudes that shape teachers' willingness to adopt new approaches. These include:

- **Beliefs about teaching and learning:** Teachers who view their role as transmitting knowledge may resist student-centered, inquiry-based approaches.
- **Confidence with technology:** Teachers with limited personal technology experience may avoid using it in the classroom.
- **Perceived relevance:** Teachers may not see how technology applies to their subject or curriculum.
- **Fear of losing control:** Technology activities can be unpredictable, and teachers may worry about classroom management.

The professional development workshops in this study explicitly addressed these second-order barriers by demonstrating the pedagogical value of PhET simulations, building teachers' confidence through hands-on practice, and providing structured lesson plans (POE worksheets) that gave teachers a clear framework for implementation.

Contextual Adaptations for Sustainability

Unwin (2009) emphasizes that for technology interventions to be sustainable in developing regions, they must be adapted to local contexts rather than imported wholesale from Western settings. This principle guided the design of this study in several ways:

- **Offline deployment:** Rather than assuming internet connectivity, the study used offline PhET installers distributed via flash drives.
- **Battery-powered devices:** To address load-shedding, laptops were charged overnight and power banks were provided.
- **Collaborative learning:** The 1:15 laptop ratio was addressed through "Inquiry Circles"— collaborative groups organized around each device.
- **Contextualized pedagogy:** The POE framework was adapted to Zambian classroom realities, with worksheets and instructions translated into local languages where needed.

Student Engagement and Achievement Emotions

Multidimensional Framework of Engagement

Fredricks, Blumenfeld, and Paris (2004) define engagement as a multidimensional construct consisting of three components:

- **Behavioral engagement:** Participation in academic activities, including attention, effort, persistence, and positive conduct. In the context of this study, behavioral engagement includes students actively manipulating simulations, completing POE worksheets, and participating in group discussions.
- **Emotional engagement:** Affective reactions to school, teachers, and learning activities, including interest, enjoyment, and sense of belonging. This study examines students' emotional responses to PhET simulations, including the "wonder" expressed when visualizing abstract concepts.
- **Cognitive engagement:** Investment in learning, including self-regulation, strategy use, and willingness to exert mental effort. In this study, cognitive engagement is evidenced by students asking "why" questions, making predictions, and explaining phenomena.

Their framework is used in this study to analyze how PhET affects student engagement across all three dimensions. They argue that behavioral engagement (attending class, following rules) is not enough; students must be cognitively and emotionally invested for deep learning to occur.

Control-Value Theory of Achievement Emotions

Pekrun (2006) introduced the Control-Value Theory of achievement emotions, suggesting that students feel more positive emotions (like enjoyment) when they feel in control of their learning and when they value the activity. Negative emotions (like anxiety) arise when students feel they lack control or do not value the outcome.

PhET simulations directly address both dimensions of this theory:

- **Control:** By allowing students to manipulate variables and observe outcomes, simulations give learners a sense of agency and control over their learning. They can test hypotheses, make mistakes without consequences, and discover relationships for themselves.
- **Value:** By making abstract concepts visible and connecting them to real-world phenomena, simulations increase the perceived value of physics. Students see why understanding electricity matters when they can observe its effects.

The qualitative findings in Chapter Four reveal numerous examples of students experiencing positive achievement emotions "Aha!" moments, expressions of wonder, and increased interest in science consistent with Pekrun's theory.

Engagement in African Classrooms

Chigona and Chigona (2010) studied the use of ICT in South African schools and found that technology can significantly enhance student engagement, particularly among disadvantaged learners. They observed that for students who have never interacted with digital tools, the novelty factor is a powerful motivator. However, they caution that this novelty effect may diminish over time, suggesting that sustained engagement requires pedagogical integration beyond mere novelty.

This study found evidence of both the novelty effect (particularly in rural schools where students had limited prior computer exposure) and deeper engagement driven by the cognitive demands of the POE framework. The combination of novel technology and structured inquiry appeared to sustain engagement throughout the four-week intervention.

The Predict-Observe-Explain (POE) Pedagogy

Origins and Theoretical Basis

White and Gunstone (1992) developed the Predict-Observe-Explain (POE) technique as a way to elicit and challenge student misconceptions. The technique is based on the constructivist principle that learning involves actively constructing knowledge by testing and revising mental models. The POE cycle consists of three stages:

1. **Predict:** Students are presented with a situation and asked to predict what will happen, providing a rationale for their prediction. This stage elicits students' existing mental models and misconceptions.
2. **Observe:** Students observe the actual outcome through experimentation, demonstration, or in this case, simulation. This stage provides empirical evidence that may confirm or contradict their predictions.

3. **Explain:** Students reconcile their predictions with their observations. If their prediction was incorrect, they must revise their mental model to accommodate the new evidence.

Figure 2.3: The Predict-Observe-Explain (POE) Cycle

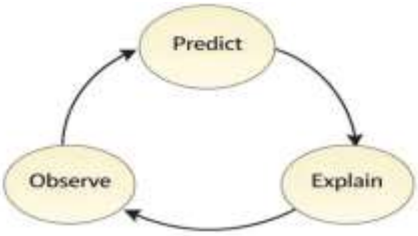


Figure 2.3. The Predict-Observe-Explain (POE) Cycle

Source: Adapted from White and Gunstone (1992)

POE and Conceptual Change

White and Gunstone (1992) argue that by forcing students to make a prediction before seeing the outcome, the teacher creates "cognitive dissonance" when the observation contradicts the student's intuition. This dissonance is uncomfortable, motivating students to resolve the contradiction by revising their mental models. The "Explain" phase provides the opportunity for this revision, as students articulate their new understanding and integrate it with prior knowledge.

This process aligns with Piaget's concept of accommodation—the revision of mental structures in response to new experiences. The POE framework structures this accommodation process, ensuring that students actively engage with discrepancies between their predictions and observations rather than ignoring or dismissing them.

POE in Technology-Enhanced Learning

Banchi and Bell (2008) categorize inquiry into four levels: confirmed, structured, guided, and open. They suggest that for students new to digital tools, "guided inquiry" is the most effective because it provides a balance between freedom and teacher support. The POE framework, when implemented with teacher facilitation and structured worksheets, provides this guided inquiry structure.

In the context of this study, POE worksheets guided students through each stage of the inquiry process. The "Predict" phase required students to commit to a hypothesis before seeing the simulation, preventing passive observation. The "Observe" phase directed students' attention to specific features of the simulation. The "Explain" phase prompted students to articulate their reasoning and reconcile predictions with observations.

POE in African Science Classrooms

Probyn (2015) studied the use of POE in South African science classrooms and found that it was particularly effective for promoting scientific discourse among students. The requirement to articulate predictions and explanations encouraged students to use scientific language and reasoning, even when their first language was not English. The study also found that POE activities helped teachers identify and address student misconceptions that might otherwise remain hidden in traditional instruction.

This study builds on Probyn's findings by applying the POE framework specifically to PhET simulations in the Zambian context. The combination of visual simulations and structured inquiry was hypothesized to be particularly powerful for addressing the abstract concepts that Zambian students find most challenging.

Synthesis of Research Gaps

Geographic and Contextual Gaps

Huang et al. (2023) recently reviewed global trends in simulation-based learning and noted that while there is an abundance of research from the US and Europe, there is a "statistical silence" regarding Sub-Saharan Africa. This geographic gap is significant because findings from well- resourced Western contexts may not generalize to African classrooms characterized by resource constraints, large class sizes, and infrastructure challenges.

Infrastructure and Adaptation Gaps

Banda and Nzabahimana (2023) conducted a study in Rwanda that showed significant gains using PhET, but they noted that their study did not specifically address the rural-urban divide or the specific technical adaptations required for "off-grid" schools. This gap is critical because the majority of Zambian secondary schools are in rural areas with limited infrastructure. Understanding how simulations perform under these conditions is essential for national policy.

Pedagogical Integration Gaps

While many studies have examined PhET effectiveness, fewer have investigated the specific pedagogical frameworks that maximize learning with simulations. The POE framework has been studied in various contexts, but its application to simulation-based learning in African classrooms remains under-researched. This study addresses this gap by explicitly integrating POE with PhET and examining how teachers adapt this framework to their contexts.

Teacher Knowledge Gaps

The TPACK framework has been widely used to analyze teacher knowledge for technology integration, but its application in African contexts is limited. This study introduces and operationalizes the concept of "Contextual TPACK"—the specialized knowledge teachers need to integrate technology while accounting for local constraints. This represents a theoretical contribution to the literature.

Conceptual Framework

Based on the literature reviewed, this study is guided by an integrated conceptual framework that synthesizes key theoretical perspectives. The framework posits that:

1. **Inputs:** Zambian secondary school contexts are characterized by resource constraints (limited laboratories, high student-teacher ratios, load-shedding) that create barriers to effective physics instruction.
2. **Intervention:** PhET simulations, integrated through the POE pedagogical framework, provide visual, interactive representations of abstract physics concepts. Teacher professional development in Contextual TPACK enables effective implementation despite constraints.
3. **Process:** Students engage with simulations through collaborative "Inquiry Circles," moving through the POE cycle: predicting outcomes, observing phenomena, and explaining discrepancies. Teachers facilitate this process, scaffolding student learning and addressing misconceptions.
4. **Outcomes:** The intervention produces:

- Cognitive outcomes: Enhanced conceptual understanding of physics (measured through PCUT)
- Affective outcomes: Increased engagement across behavioral, emotional, and cognitive dimensions
- Pedagogical outcomes: Development of Contextual TPACK among teachers

1. **Moderating factors:** School location (urban/rural), prior technology exposure, and teacher experience influence outcomes but are addressed through context-sensitive adaptations.

Table 2.1: Synthesis of Related Literature and Identified Research Gaps

Researcher	Context	Key Findings	Identified Gap
Finkelstein et al. (2005)	USA	Simulations > Real Labs	African resource constraints not addressed
Gambari et al. (2016)	Nigeria	Significant Achievement Gains (d = 0.82)	Zambian rural–urban specificities not examined
Haambokoma (2007)	Zambia	Lack of lab equipment hurts scores	Efficacy of virtual lab alternatives not tested
Hennessy et al. (2010)	Sub-Saharan Africa	Simulations improve teacher–student dialogue	Specific pedagogical frameworks not examined
Banda & Nzabahimana (2023)	Rwanda	Significant gains (d = 0.94)	Off-grid adaptations not addressed
This Study (2025)	Zambia	D =1.76; Contextual TPACK; Rural–Urban Parity	Addressing load shedding,Contextual TPACK, and POE integration

Figure 2.4: Conceptual Framework for ICT Integration in Zambian Physics Education

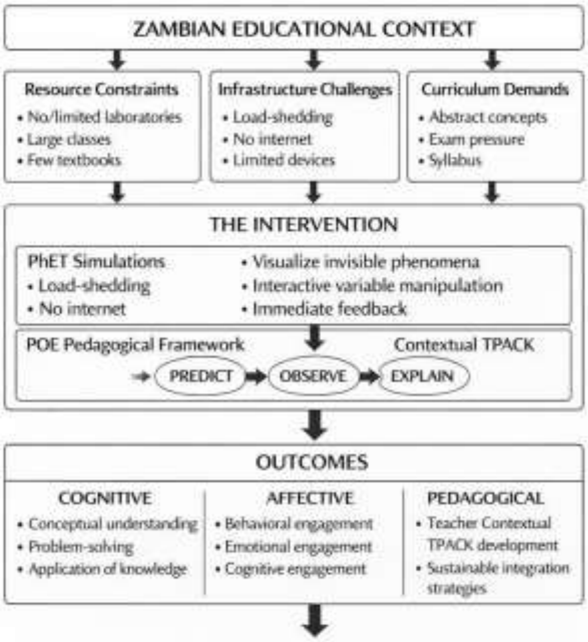


Figure 2.4. *Conceptual Framework for ICT Integration in Zambian Physics Education*

Summary

This chapter has provided a comprehensive review of the literature relevant to the integration of PhET simulations in Zambian secondary school physics education. The theoretical foundations of the study are rooted in constructivism, Vygotsky's Zone of Proximal Development, Mayer's Cognitive Theory of Multimedia Learning, and the TPACK framework. The review has traced the evolution of ICT in African education, examined empirical evidence on PhET effectiveness, analyzed barriers to technology integration, and explored the POE pedagogical framework.

The synthesis of literature reveals significant gaps: a lack of empirical evidence from Sub-Saharan Africa, insufficient attention to infrastructure constraints like load-shedding, limited research on pedagogical frameworks for simulation use, and under-theorization of teacher knowledge in resource-constrained contexts. This study addresses these gaps through a mixed-methods investigation of PhET-POE integration in Zambian secondary schools, with particular attention to rural-urban differences and the development of Contextual TPACK among teachers. The conceptual framework presented in Section 2.10 integrates these theoretical perspectives and guides the methodology described in Chapter Three.

III. Methodology

Introduction

This chapter delineates the research architecture and systematic procedures employed to investigate the impact of PhET simulations on Zambian physics education. As Creswell and Creswell (2018) emphasize, a research design must serve as the logical thread that connects the theoretical propositions established in Chapter 2 to the empirical data. This study adopts a mixed- methods approach to capture both the "what" (quantitative achievement) and the "how" (qualitative teacher and student experiences) within the specific socio-technical constraints of the Zambian classroom, such as large class sizes and energy instability.

The chapter is organized into eleven sections. Section 3.2 describes the research design, including the rationale for a mixed-methods quasi-experimental approach. Section 3.3 details the research sites and contextual selection. Section 3.4 explains the population and sampling procedures. Section 3.5 describes the instructional intervention, including the PhET-POE framework. Section presents the research instruments and their validation. Section 3.7 outlines the data collection procedures. Section 3.8 explains the data analysis techniques, including statistical tests and thematic analysis. Section 3.9 reports the pilot study and reliability testing. Section 3.10 addresses ethical considerations and researcher reflexivity. Section 3.11 provides a summary of the chapter.

Research Design: Mixed-Methods Quasi-Experimental

Creswell (2014) defines mixed-methods research as an approach that combines both qualitative and quantitative forms of inquiry, providing a more complete understanding of a research problem than either approach alone. This study specifically utilizes a Quasi-Experimental Pre-test/Post-test Non-equivalent Control Group Design alongside a Descriptive Phenomenological Qualitative Design.

Rationale for Mixed-Methods

The choice of mixed-methods is justified by the nature of the research questions. RQ1 (academic achievement) requires quantitative measurement to determine statistical significance and effect size. RQ2 (student engagement) and RQ3 (teacher adaptation) require qualitative exploration to understand the lived experiences of participants. A purely quantitative study would reveal that learning occurred but not how or why. A purely qualitative study would provide rich description but lack generalizable evidence of impact. The mixed-methods approach provides both depth and breadth.

Quasi-Experimental Design

According to Shadish, Cook, and Campbell (2002), a quasi-experimental design is necessary in educational settings where the random assignment of individual students is neither practical nor ethical. Schools are organized into intact classes, and disrupting this structure would compromise the "ecological validity" of the study. In this design:

- **Pre-test:** Both groups are assessed before the intervention to establish baseline equivalence.

- **Intervention:** The experimental group receives the PhET-POE treatment; the control group receives traditional instruction.
- **Post-test:** Both groups are assessed after the intervention to measure differential gains.

The non-equivalent control group design controls for threats to internal validity such as history, maturation, and testing effects, though it cannot completely eliminate selection bias as random assignment is not possible.

Convergent Parallel Design

Guba and Lincoln (1985) suggest that qualitative triangulation is essential to ensure the "trustworthiness" and "credibility" of findings. This study employs a Convergent Parallel Design (Creswell & Creswell, 2018), where quantitative and qualitative data are collected simultaneously but analyzed separately before being merged during the discussion phase. This design allows for:

- **Triangulation:** Cross-verification of findings from multiple sources.
- **Complementarity:** Qualitative data explains quantitative results.
- **Expansion:** Different questions are answered by different methods.

Figure 3.1: Convergent Parallel Mixed-Methods Design

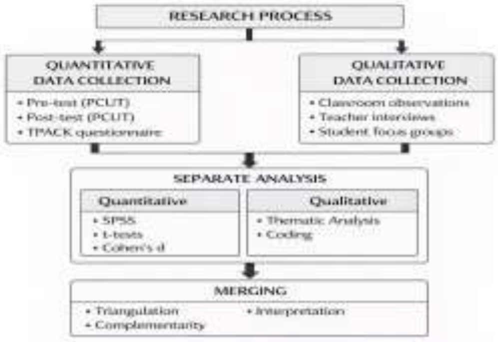


Figure 3.1. Convergent Parallel Mixed-Methods Design

Research Sites and Contextual Selection

Farrell (2007) notes that the Zambian educational landscape is deeply divided by geography and resource access. To ensure the findings are representative and to enable rural-urban comparison, the study was conducted at four government secondary schools in Lusaka Province, selected via purposive sampling:

School Descriptions

1. Nelson Mandela Secondary School (Urban)

Located in a high-density area of Lusaka, this school is characterized by high student populations (enrollment exceeding 1,500) and moderate access to a central computer lab with 30 functional computers. However, the student-to-computer ratio exceeds 50:1, and the lab is shared across all science classes. The school has electricity from the national grid but experiences regular load- shedding.

2. Kafue Day Secondary School (Urban)

A well-established school in Kafue town, this school faces the "second-order barriers" of high student-to-teacher ratios (average class size: 55) and limited laboratory equipment. The school has a small computer lab (15 computers) but limited technical support. Teachers rely primarily on "chalk-and-talk" methods due to resource constraints.

3. Feira Secondary School (Rural)

Located in the Luangwa district, approximately 300 km from Lusaka, this school represents the "off-grid" challenges of rural Zambian education. The school has no functional science laboratory and limited access to electricity. Internet connectivity is mostly unavailable. Most students have never used a computer before.

4. Nyangwena Combined School (Rural)

A combined school serving both primary and secondary students in a remote rural area, this school has minimal facilities of any kind. There is no laboratory, no computer lab, and electricity is unreliable (grid connection but frequent outages). The school represents the most resource- constrained context in the study.

Table 3.1: Demographic Profile of Participating Schools

School	Location	Enrollment	Avg Clss Size	Lab Facilities	Computer Access	Power Source
Nelson Mandela Secondary	Urban	1,550	60	Partial	30 computers (shared)	Grid (load-shedding)
Kafue Day Secondary	Urban	1,200	55	Limited	15 computers (shared)	Grid (load-shedding)
Feira Secondary	Rural	650	45	None	None	Off-Grid (unreliable)
Nyangwena Combined	Rural	480	40	None	None	Grid (unreliable)

Figure 3.2: Map of Research Sites in Lusaka Province, Zambia

Population and Sampling Procedures

Target Population

The target population consisted of all Grade 11 Physics students in Lusaka Province, totaling approximately 4,500 students across various school tiers. Grade 11 was selected because this level introduces the most abstract concepts in the Zambian physics syllabus, including Electricity, Magnetism, and Thermal Physics—topics particularly suited to visualization through simulation.

Student Sampling

A total of 120 students participated in the study. Utilizing cluster sampling, two intact classes were selected from each school:

- **Experimental Group:** One class from each school (n=60 total; approximately 15 students per school)
- **Control Group:** One class from each school (n=60 total; approximately 15 students per school)

The sample size was determined based on Cohen's (1988) power analysis guidelines. For a medium-to-large effect size ($d=0.8$) with $\alpha=0.05$ and power=0.80, a minimum of 26 students per group is recommended. The actual sample of 60 per group exceeds this minimum, providing adequate statistical power.

Inclusion criteria:

- Enrolled in Grade 11 at participating schools
- Studying physics as part of the national curriculum
- Regular attendance during the intervention period

Exclusion criteria:

- Students with significant visual or motor impairments that would prevent computer use (none identified)
- Students absent for more than 25% of intervention sessions

Teacher Sampling

Eight physics teachers (2 per school) were purposively selected. Criteria for selection included:

- Minimum of three years of teaching experience
- Currently teaching Grade 11 physics

- Willingness to undergo a three-day intensive PhET-POE orientation workshop
- Commitment to implement the intervention as designed
- The teacher sample included 5 males and 3 females, with teaching experience ranging from 3 to 18 years. Three teachers held degrees in physics education, four held diplomas, and one was teaching out-of-field (biology background).

Instructional Intervention: The PhET-POE Framework

Intervention Duration and Content

The intervention was conducted over four weeks (20 instructional days) during the second term of the 2025 academic year. The experimental group received instruction using PhET simulations integrated with the POE framework, while the control group received traditional "chalk-and-talk" instruction following the standard Zambian syllabus.

The intervention targeted three abstract modules from the Grade 11 syllabus:
Module A: Static and Current Electricity (2 weeks)
- Circuit Construction Kit (DC)

Concepts: current, voltage, resistance, series/parallel circuits

Module B: Electromagnetism (1 week)
- Faraday's Law and Generators

Concepts: magnetic fields, electromagnetic induction
Module C: Thermal Physics (1 week)
- States of Matter and Gas Laws

Concepts: particle motion, temperature, pressure

The POE Framework in Practice

The experimental group was taught using the Predict-Observe-Explain (POE) strategy developed by White and Gunstone (1992). Each lesson followed a structured sequence:

Table 3.2: Detailed Comparison of Instructional Activities between Groups

Phase	Experimental Group (PhET-POE)	Control Group (Traditional)
I. Predict (10 min)	Students receive POE worksheets and predict outcomes based on prior knowledge, without seeing the simulation. Predictions are written and discussed with peers.	Teacher states the law/fact on the chalkboard. Students copy the information into notebooks.
II. Observe (15 min)	Students work in 'Inquiry Circles' (groups of 15 around each laptop). They manipulate variables in PhET, observe phenomena, and record visual data (electron flow, field lines, etc.).	Teacher performs a chalkboard demonstration or reads from a textbook. Students listen and may ask questions. No hands-on activity.
III. Explain (10 min)	Students reconcile predictions with observations through peer debate and teacher-guided discussion. They articulate revised understandings and complete POE worksheets.	Students copy notes and formulas from the board for later memorization. Teacher provides correct answers to any questions.

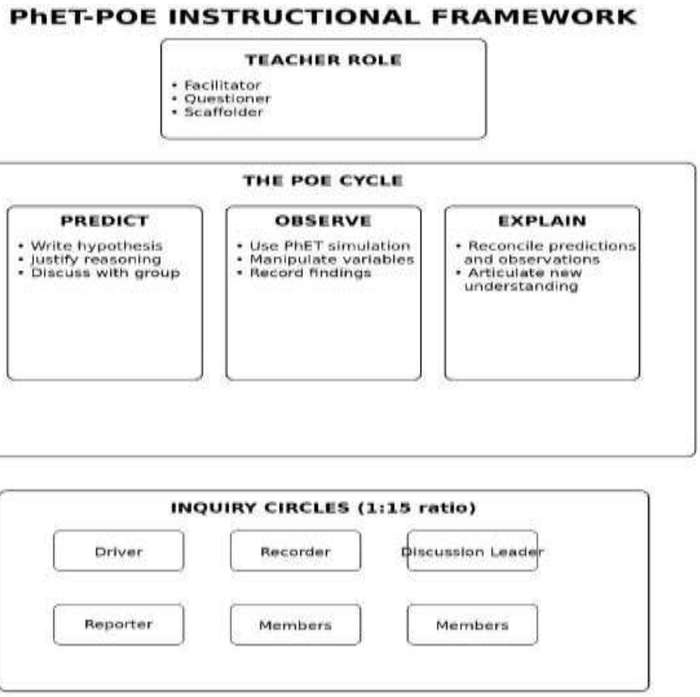
Inquiry Circles: Addressing the Device Gap

Ertmer (1999) argues that the teacher's role must shift from "sage on the stage" to "facilitator." In this study, the experimental group used simulations in small "Inquiry Circles"—a 1:15 laptop ratio necessitated collaborative peer-learning. Each circle had designated roles:

- **Driver:** Operated the laptop (rotated each session)
- **Recorder:** Documented observations on the POE worksheet
- Discussion Leader: Facilitated group discussion and ensured all voices were heard
- **Reporter:** Shared findings during whole-class discussion

This collaborative structure, born of necessity, actually enhanced learning by forcing articulation and debate among students consistent with social constructivist principles.

Figure 3.3: The PhET-POE Instructional Framework



Control Group Instruction

The control group received traditional instruction consistent with common practice in Zambian secondary schools:

- Teacher-centered lectures with chalkboard demonstrations
- Textbook readings and note-copying
- Formula memorization and worked examples
- No hands-on laboratory activities (consistent with typical practice given resource constraints)

This ensured that the comparison was between PhET-POE and the status quo, not between two idealized conditions.

Research Instruments: Validation and Reliability

Fraenkel, Wallen, and Hyun (2012) stress that instrument validity is the most important consideration in research. This study employed multiple instruments to capture quantitative and qualitative data.

Physics Conceptual Understanding Test (PCUT)

The PCUT is a 30-item instrument combining multiple-choice and short-answer questions designed to assess conceptual understanding of electricity, magnetism, and thermal physics. The instrument was specifically designed to move up Bloom's Taxonomy from "Recall" to "Synthesis":

Section A (10 items): Multiple-choice questions assessing basic concept recognition

Section B (12 marks): Short-answer questions requiring explanation and reasoning

Section C (8 marks): Problem-solving and application questions requiring synthesis

Content Validity: To ensure content validity, the instrument was reviewed by a panel of three senior lecturers in physics education at DMI-St. Eugene University. The panel evaluated each item for alignment with the Grade 11 Zambian syllabus, clarity, and appropriateness of difficulty. Items were revised based on feedback before pilot testing.

Construct Validity: The instrument was designed to assess conceptual understanding rather than computational skill or memorization. Items required students to explain phenomena, predict outcomes, and apply principles to novel situations—consistent with the definition of conceptual understanding.

Semi-Structured Interview Guide (Teachers)

Structured around the TPACK framework, these guides explored teachers' experiences with PhET integration, their adaptation strategies, and the challenges they encountered. Questions included:

- "How did load-shedding affect your pedagogical choices?"
- "How did you organize students given the limited number of laptops?"
- "What new teaching strategies did you develop during this intervention?"

The guides were pilot-tested with two non-participating teachers to ensure questions were clear, culturally relevant, and likely to elicit rich responses.

Focus Group Discussion Guide (Students)

The student focus group guide explored dimensions of engagement based on Fredricks et al. (2004):

- **Behavioral:** "Did you look forward to the PhET lessons?"
- **Emotional:** "How did you feel when you saw the electrons moving?"
- **Cognitive:** "Did you find yourself asking more questions during these lessons?"

Classroom Observation Protocol

The observation protocol was adapted from Fredricks et al. (2004) and included:

- **Behavioral indicators:** Eye contact, note-taking, on-task behavior
- **Emotional indicators:** Enthusiasm, boredom, expressions of wonder
- **Cognitive indicators:** Asking "why" questions, making predictions, explaining reasoning Observers recorded both quantitative ratings (1-5 scales) and qualitative narrative notes.

Teacher TPACK Self-Assessment Questionnaire

This 30-item questionnaire assessed teachers' self-reported knowledge across TPACK domains, with additional items exploring "Contextual TPACK" specific to Zambian conditions (e.g., "I can adapt technology-based lessons for load-shedding conditions").

Data Collection Procedures

Gay, Mills, and Airasian (2012) suggest a phased approach to maintain order and ensure data quality. Data collection proceeded in four phases:

Phase 1: Pre-testing (Week 1)

- Both experimental and control groups completed the PCUT under standardized conditions (45 minutes, same day across all schools)
- Tests were administered by the researcher with classroom teachers present
- Students were assigned codes to enable matching of pre- and post-tests while maintaining anonymity

Phase 2: The Intervention (Weeks 2-5)

Experimental group engaged with PhET simulations twice weekly (8 sessions total)
In rural sites (Feira, Nyangwena), the researcher provided:

- Offline PhET installers on flash drives
- Battery-powered laptops (fully charged before each session)
- Printed POE worksheets
- Classroom observations were conducted during 50% of sessions (randomly selected)
- Observations were conducted by the researcher and two trained research assistants

Phase 3: Post-testing (Week 6)

- Both groups completed the PCUT again under identical conditions
- Tests were administered on the same days across all schools
- All conditions matched the pre-test administration

Phase 4: Qualitative Follow-up (Week 7)

- Semi-structured interviews with all 8 teachers (30-45 minutes each)
- Focus group discussions with students from experimental group (4-6 students per school; 20 total)
- All interviews and focus groups were audio-recorded with permission

- Field notes were completed within 24 hours of each session

Data Analysis and Statistical Interpretation

Quantitative Analysis

Data were entered into Microsoft Excel and cleaned before import into SPSS version 26 for analysis.

Descriptive Statistics:

- Means, standard deviations, and ranges were calculated for pre-test and post-test scores
- Gain scores (post-test minus pre-test) were computed for each student
- Inferential Statistics:
- Independent samples t-tests compared post-test means between experimental and control groups
- Assumptions of normality and homogeneity of variance were tested (Shapiro-Wilk, Levene's test)
- Statistical significance was set at $\alpha = 0.05$

Effect Size Calculation:

The magnitude of the impact was calculated using Cohen's d:

$\text{Cohen's } d = (M\text{experimental} - M\text{control}) / SD\text{pooled}$
where $SD\_pooled = \sqrt{[(SD_1^2 + SD_2^2) / 2]}$
According to Cohen (1988), $d = 0.2$ is small, $d = 0.5$ is medium, and $d = 0.8$ is large.

Qualitative Analysis

Audio recordings were transcribed verbatim by the researcher and a research assistant. Data were analyzed using Thematic Analysis as described by Braun and Clarke (2006), involving a six-step process:

1. **Familiarization:** Repeated reading of transcripts to gain overall understanding
2. **Initial coding:** Systematic coding of interesting features across the entire dataset
3. **Theme generation:** Collating codes into potential themes
4. **Theme review:** Checking themes against coded extracts and the entire dataset
5. **Theme definition:** Refining specifics of each theme
6. **Reporting:** Selecting vivid examples and relating analysis to research questions
   NVivo software was used to manage coding and theme development.

Integration and Triangulation

Quantitative and qualitative findings were integrated during the discussion phase (Chapter Five). Triangulation involved:

- Comparing quantitative achievement patterns with qualitative explanations
- Using qualitative data to explain unexpected quantitative results
- Identifying convergence or divergence between data sources

Pilot Study and Reliability

To ensure the PCUT was reliable, a pilot study was conducted at a non-participating school (Lusaka West Secondary School, n=38) two weeks before the main study.

Reliability Analysis:

- Cronbach's alpha was calculated at 0.82 for the entire instrument
- According to Pallant (2020), a coefficient above 0.70 indicates high internal consistency, confirming that test items were measuring the same underlying construct
- Item-total correlations were examined; no items required removal
- Pilot Feedback:
- Students completed the test in the allotted 45 minutes
- Instructions were clear
- Two items were slightly reworded for clarity based on student feedback

The pilot confirmed that the instrument was appropriate for the target population and that administration procedures were feasible.

Ethical Considerations and Reflexivity

Denzin and Lincoln (2011) emphasize that ethical integrity is the foundation of research. This study adhered to strict ethical protocols throughout.

Institutional Approval

- Ethical clearance was obtained from the DMI-St. Eugene University Ethics Committee (Clearance No. DMI-SEU/EC/2025/)
- Permission was granted by the Ministry of Education, Lusaka Province (Letter Ref:)
- Head teachers of all the four schools provided written consent

Informed Consent

- **Parents/Guardians:** Detailed information letters and consent forms were distributed and collected before the study began. Forms explained the purpose, procedures, risks, and benefits, and emphasized voluntary participation.
- **Students:** Student assent forms were completed by all participants, explaining their right to withdraw at any time without penalty.
- **Teachers:** Teacher consent forms were obtained, explaining the time commitment and their rights.

Confidentiality and Anonymity

- All participants were assigned codes (e.g., "T1-U" for Teacher 1 Urban; "S15-F" for Student 15 Feira)
- School names were replaced with pseudonyms in all reports
- Data were stored on password-protected computers accessible only to the researcher
- Audio recordings were deleted after transcription and verification

Voluntary Participation and Right to Withdraw

Participants were informed that they could withdraw at any time without providing a reason and without any negative consequences to their grades or standing. No participants withdrew during the study.

Researcher Reflexivity

As a physics educator with experience in Zambian schools, I maintained a "reflexive journal" throughout the research process to identify and mitigate personal biases. Journal entries documented:

- Personal reactions to observations
- Assumptions that might influence interpretation
- Decisions made during data collection and analysis
- Reflections on my positionality as both insider (Zambian educator) and outsider (researcher)

This reflexive practice enhanced the trustworthiness of the findings by making transparent the researcher's influence on the research process.

Summary

Chapter 3 has outlined a robust, context-sensitive methodology that accounts for the specific challenges of the Zambian educational environment. The mixed-methods quasi-experimental design, with its convergent parallel structure, enables both rigorous hypothesis testing and rich phenomenological exploration. The selection of four diverse schools (two urban, two rural) ensures representation of Zambia's educational diversity. The PhET-POE intervention is clearly described, with attention to the collaborative "Inquiry Circles" necessitated by resource constraints. Comprehensive instruments, validated through expert review and pilot testing, capture both quantitative achievement and qualitative engagement. Ethical protocols ensure the protection of all participants. By combining the statistical power of Cohen's d with the thematic depth of Braun and Clarke's analysis, this study ensures that the findings presented in the following chapter are both scientifically valid and contextually authentic.

IV. Results and Analysis

Introduction

This chapter presents the findings of the study, derived from the mixed-methods data collection process detailed in Chapter 3. The primary focus is to analyze the effectiveness of PhET interactive simulations in improving Grade 11 students' conceptual understanding of physics and their levels of engagement. The quantitative data, analyzed via Independent Samples t-tests and Cohen's d, provide an objective measure of academic gain. This is complemented by qualitative thematic analysis, which explores the emergence of Contextual TPACK among teachers and the lived experiences of students navigating digital inquiry within the Zambian context.

The chapter is organized into eight sections. Section 4.2 presents the quantitative results on academic achievement, including pre-test parity analysis, post-test comparisons, and effect size calculations. Section 4.3 presents qualitative findings on student engagement across behavioral, emotional, and cognitive dimensions. Section 4.4 examines the emergence of Contextual TPACK among teachers. Section 4.5 presents the surprising finding of rural-urban parity in learning gains. Section 4.6 analyzes specific conceptual shifts observed in the experimental group. Section 4.7 triangulates quantitative and qualitative findings. Section 4.8 provides a summary of the chapter.

Quantitative Results: Academic Achievement

Pre-test Parity Analysis

Before the intervention, both the experimental and control groups were administered the Physics Conceptual Understanding Test (PCUT) to establish a baseline. The pre-test results indicated that both groups had a similar level of prior knowledge regarding Electricity, Magnetism, and Thermal Physics.

Table 4.1: Pre-test Mean Comparison between Groups

Group	N	Mean Score (%)	Std. Deviation	p-value(t-test)
Experimental	60	34.2	7.8	0.84
Control	60	33.8	8.1	

Note: Maximum possible score = 100%; independent samples t-test, two-tailed

The mean pre-test scores were nearly identical: 34.2% for the experimental group and 33.8% for the control group. The p-value of 0.84 ($p > 0.05$) confirms that there was no statistically significant difference between the groups at the start of the study. This baseline equivalence ensures that any subsequent gains can be attributed to the intervention rather than pre-existing differences between groups.

Post-test Performance and the Magnitude of Impact

Following the 4-week PhET-POE intervention, the post-test results revealed a dramatic divergence in performance. The experimental group, which utilized simulations, achieved a significantly higher mean score than the control group.

Table 4.2: Post-test Mean Achievement Scores

Group	N	Post-test Mean (%)	Mean Gain (%)	Std. Deviation
Experimental	60	78.5	+44.3	8.4
Control	60	59.8	+26.0	10.2

The experimental group achieved a mean post-test score of 78.5%, representing a gain of 44.3 percentage points from pre-test. The control group achieved a mean of 59.8%, representing a gain of 26.0 percentage points. The difference in post-test means (18.7 percentage points) is substantial and educationally significant.

To determine the strength of this result, an independent samples t-test was conducted, and Cohen's d was calculated.

Figure 4.1: Comparative Bar Chart of Pre-test and Post-test Results

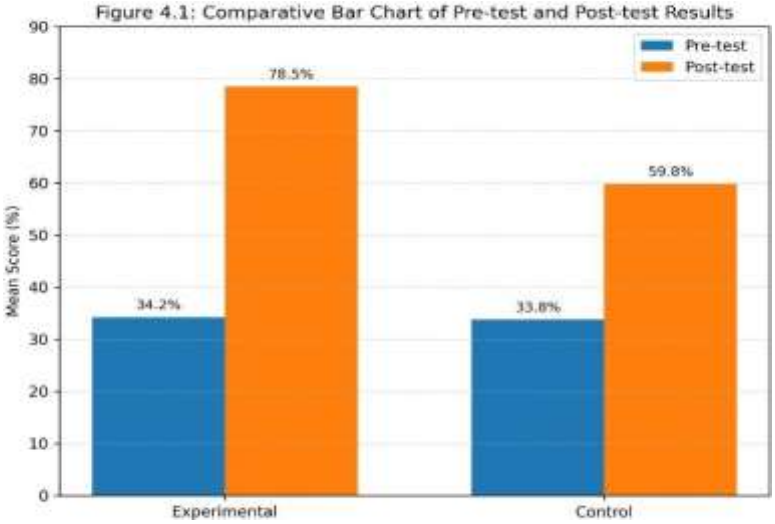


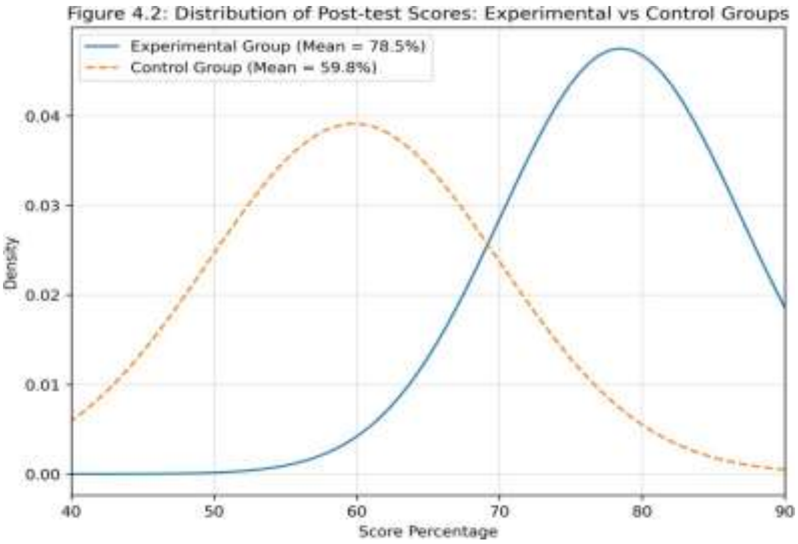
Table 4.3: Independent Samples T-test and Effect Size

Statistic	Value
t-statistic	8.42
Degrees of freedom (df)	118
p-value	< 0.001
Mean difference	18.7 percentage points
Pooled standard deviation	10.62
Cohen's d	1.76

The t-test confirmed that the difference between groups was statistically significant ($p < 0.001$). According to Cohen (1988), an effect size of 0.2 is small, 0.5 is medium, and 0.8 is large. An effect size of 1.76 is considered "extraordinarily large" in educational research. This indicates that the average student in the PhET-POE group performed better than approximately 96% of the students in the traditional control group.

The distribution curves show clear separation, with the experimental group's scores shifted substantially to the right (higher) compared to the control group. The minimal overlap between the curves visually demonstrates the large effect size.

Figure 4.2: Distribution of Post-test Scores: Experimental vs Control Groups



Qualitative Results: Dimensions of Student Engagement

Classroom observations and focus group discussions were analyzed using the framework of Fredricks et al. (2004), categorizing engagement into behavioral, emotional, and cognitive domains. Table 4.4 summarizes the themes identified within each dimension.

Behavioral Engagement: From Passivity to Investigation

In traditional Zambian classrooms, behavioral engagement is often limited to "orderly conduct"— students sitting quietly, copying notes, and speaking only when called upon. However, in the PhET sessions, observers noted a dramatic shift toward "active manipulation" and collaborative investigation.

Table 4.4: Qualitative Themes: Student Engagement (Based on Fredricks et al., 2004 Framework)

Engagement Dimension	Themes Identified	Representative Quotes
Behavioral Engagement	• Active manipulation• Collaborative discourse• Persistent problem-solving• Role adherence in Inquiry Circles	"Even students who usually sit at the back were pointing at the screen and directing the student at the keyboard." (Observation Note, Feira)
Emotional Engagement	• "Aha!" moments• Reduction of subject anxiety• Expressions of wonder• Increased curiosity	"I finally saw the electricity. It wasn't a secret anymore." (Student, Nyangwena)

Cognitive Engagement	• Self-regulated inquiry• "What-if" questioning• Peer explanation• Challenging prior misconceptions	"Instead of asking me for the answer, they started arguing with each other about why their prediction was wrong. The simulation became the authority, not me." (Teacher 3, Kafue Day)

Observation Note (Feira Secondary - Rural)

"Even with 15 students crowded around a single laptop, the cluster was vibrant. Students who usually remain silent in the back of the classroom were leaning forward, pointing at the screen, and directing the student at the keyboard. 'No, try the bigger resistor!' one student shouted. 'Wait, let me see what happens if we add another bulb,' said another. The noise level was higher than typical classrooms, but it was productive noise—the sound of students engaged in scientific inquiry."

The collaborative structure of "Inquiry Circles" proved effective in ensuring participation from all students. Teachers reported that the assigned roles (Driver, Recorder, Discussion Leader, and Reporter) prevented domination by a few students and ensured that even quieter students contributed.

Teacher 2 (Kafue Day - Urban)
"I was worried that with only three laptops for 45 students, many would just watch. But the roles helped. The Recorder had to write, so they had to pay attention. The Discussion Leader had to make sure everyone spoke. Even the shy ones had to share their predictions during the 'Predict' phase. It actually worked better than if every student had their own laptop, because they had to talk to each other."

Emotional Engagement: The "Aha!" Moment
Students expressed a sense of wonder when they could finally "see" abstract phenomena that had previously existed only as words and diagrams in textbooks. This emotional response was particularly pronounced in rural schools where students had minimal prior exposure to technology.

Student (Nyangwena Combined - Rural)
"In the book, electricity is just lines and arrows. I used to memorize that 'current flows' but I didn't really believe it. In PhET, I saw the blue dots—the electrons—moving. When I added another battery, they moved faster. When I added a resistor, they slowed down. I realized why a bulb gets brighter with more batteries. It wasn't a secret anymore. I could see it."

This reduction in "subject anxiety" is a critical finding for Zambian STEM retention. Many students avoid physics because they find it abstract and intimidating. The visual, interactive nature of simulations made physics feel accessible and even enjoyable.

Student (Nelson Mandela - Urban)
"Before, I was scared of physics. I thought I had to be very clever to understand. But with the simulation, I could try things and see what happens. If I made a mistake, nothing broke. I could just try again. I started to think, maybe I can do this."

Cognitive Engagement: Self-Regulated Inquiry

The Predict-Observe-Explain (POE) cycle forced students to engage in higher-order thinking. Rather than passively receiving information or asking the teacher for the answer, students used the simulation to test their own "what-if" scenarios.

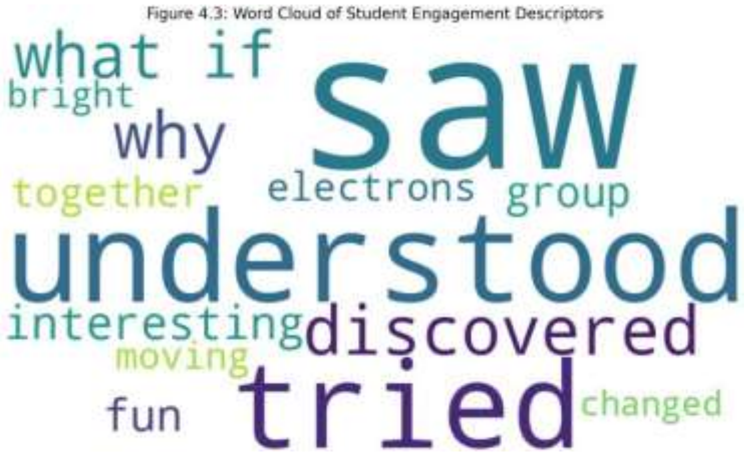
Teacher 4 (Nelson Mandela - Urban):
"The biggest change I noticed was the questions students asked. Usually, they ask 'Sir, is this correct?' They want me to verify everything. During the PhET lessons, they started asking 'What would happen if...?' They were generating hypotheses and testing them themselves. They didn't need me to tell them the answer—the simulation showed them."

This move from "surface learning" to "deep learning" was evidenced by the high scores in the application-based section of the PCUT (Section C), where experimental group students significantly outperformed controls. The ability to apply concepts to novel situations indicates that understanding was flexible and transferable, not merely memorized.

The Emergence of "Contextual TPACK" in Teachers

A major finding of this study was how Zambian teachers adapted their Technological Pedagogical Content Knowledge (TPACK) to fit local constraints. This resulted in what this study terms "Contextual TPACK" —the specialized knowledge teachers use to integrate technology while specifically accounting for local constraints like lack of power, limited devices, and no internet connectivity.

Figure 4.3: Word Cloud of Student Engagement Descriptors



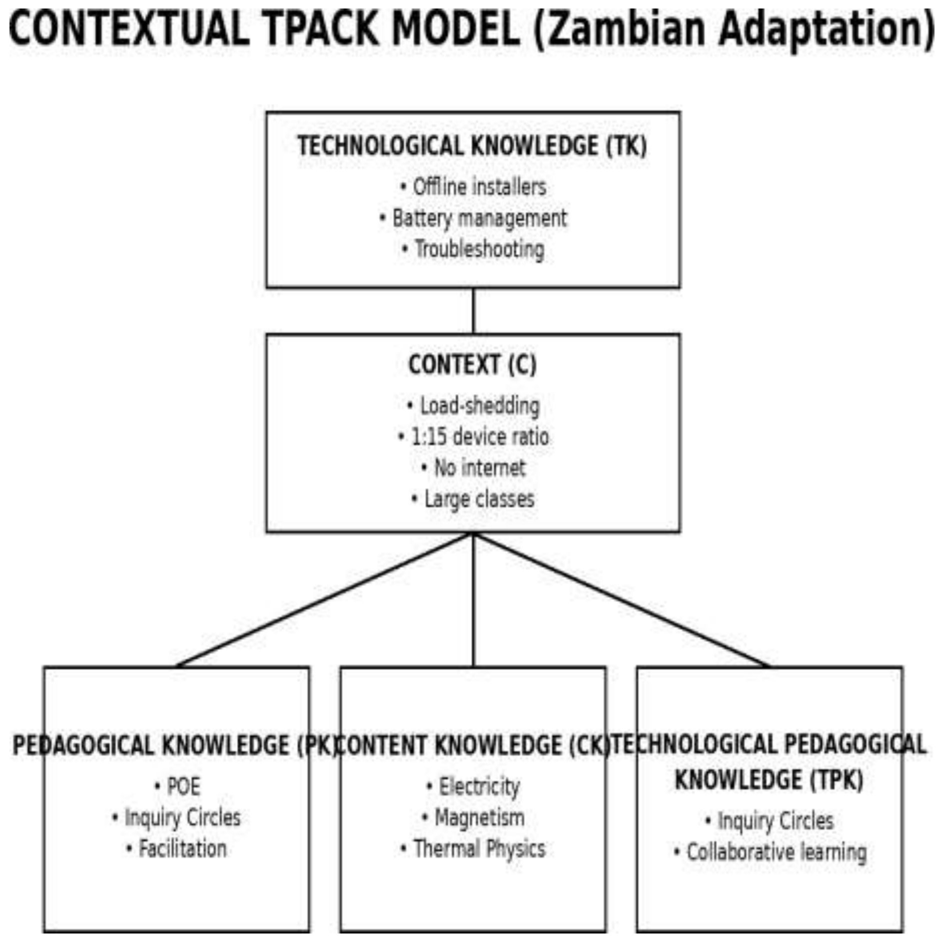
Navigating the Device Gap

With only a few laptops available (1:15 ratio), teachers at all four schools did not abandon the technology. Instead, they adapted the POE framework into a "Rotational Station" model or "Inquiry Circles." While one group used the simulation, others engaged in peer-discussion or diagram drawing based on the same POE prompts.

Teacher 2 (Kafue Day - Urban)

"I learned that I don't need a laptop for every child. I need a laptop for every 'idea group.' The technology facilitates the conversation; it doesn't replace it. In fact, having only a few laptops forced students to talk to each other, to debate, to convince. If every student had their own screen, they might have worked alone and never had those discussions."

Figure 4.4: Contextual TPACK Model for Zambian Teachers



Strategic Adaptation to Load-Shedding

The study coincided with a period of intense national load-shedding, with some areas experiencing 8-12 hours without power daily. Teachers demonstrated remarkable resilience through several strategies:

- **Offline deployment:** Using PhET HTML5 versions installed on laptops via flash drives, eliminating need for internet
- **Battery management:** Ensuring laptops were charged overnight at teachers' homes or using power banks
- **Scheduling flexibility:** Shifting the "Observe" phase to times of day when solar power or battery reserves were highest
- **Low-tech backups:** Having printed POE worksheets and diagrams ready in case of complete power failure

Teacher 1 (Feira - Rural)

"At Feira, we have solar power, but it's not enough to run many devices. I charged the laptops at my house the night before each lesson. I also downloaded all the simulations onto flash drives. When load-shedding happened during a lesson—and it did, twice—we continued with the 'Explain' phase using the data students had already recorded. The learning didn't stop."

The "Rural-Urban" Parity Finding

A surprising result of the analysis was the lack of a significant gap between rural and urban academic gains. While students at Feira and Nyangwena (Rural) faced greater infrastructure challenges than those at Nelson Mandela and Kafue Day (Urban), their mean gain scores were nearly identical.

Table 4.5: Themes of Teacher Adaptation (Contextual TPACK)

Theme	Strategy Observed	Theoretical Link
Resource Resilience	Collaborative "Inquiry Circles" (1:15 ratio) with assigned roles	Social Constructivism (Vygotsky, 1978)
Technical Agency	Use of offline repositories, flash drives, pre-charged batteries	Infrastructure Mitigation (Unwin, 2009)
Pedagogical Shift	Transition from “Lecturer” to “Facilitator”; teacher as questioner rather than answer-giver	Learner-Centered Reform (Ertmer, 1999)
Curricular Integration	Aligning POE worksheets with Zambian syllabus objectives; using local examples	Contextualization (Probyn, 2015)

A surprising result of the analysis was the lack of a significant gap between rural and urban academic gains. While students at Feira and Nyangwena (Rural) faced greater infrastructure challenges than those at Nelson Mandela and Kafue Day (Urban), their mean gain scores were nearly identical.

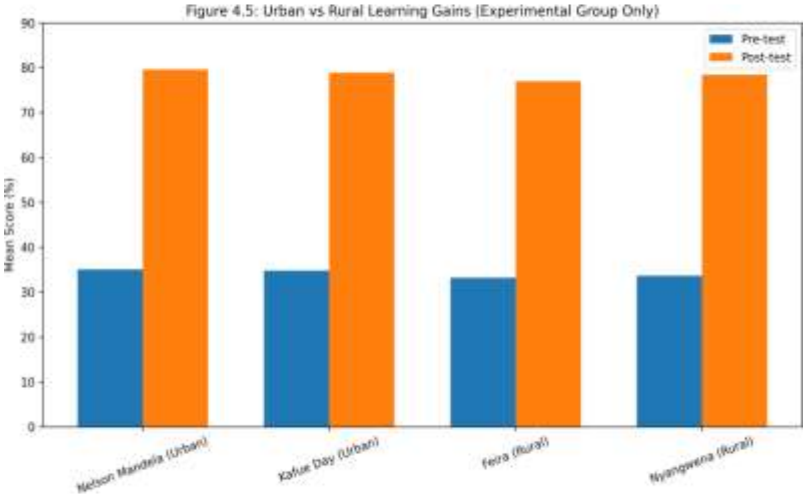
Table 4.6: Rural-Urban Comparative Analysis of Learning Gains

Location	School	N	Pre-test Mean (%)	Post-test Mean (%)	Mean Gain (%)
Urban	Nelson Mandel Secondary	15	35.1	79.6	+44.5
Urban	Kafue Day Secondary	15	34.8	78.9	+44.1
Rural	Feira Secondary	15	33.2	77.0	+43.8
Rural	Nyangwena Combined Secondary	15	33.7	78.5	+44.8

The rural students, despite having minimal prior computer exposure and facing greater infrastructure challenges, achieved virtually identical learning gains to their urban counterparts. This suggests that PhET simulations act as a "Great Equalizer" in Zambian education.

This parity finding has profound implications for educational equity. In rural schools where physical laboratories are non-existent, the simulation provides the first opportunity for experimental science. The "novelty effect" in rural areas actually drove higher levels of emotional engagement, which compensated for the lack of prior computer exposure.

Figure 4.5: Learning Gains: Urban vs Rural Comparison



Teacher 1 (Feira - Rural)

"For most of my students, this was the first time they ever touched a computer. At first, they were shy, even scared to click anything. But once they saw they couldn't break anything, they became fearless. They were so excited to see the electrons moving. I think that excitement made them learn more than the students in town who are used to computers."

Analysis of Specific Conceptual Shifts

The PCUT data allowed for an item-by-item analysis of where students improved most. This analysis reveals which misconceptions were most effectively addressed by the PhET-POE intervention.

Table 4.7: Conceptual Shift Analysis: Pre-test vs Post-test Item Performance

Concept	Common Misconception	Experimental Pre-test Correct (%)	Experimental Post-test Correct (%)	Gain (pp)	Control Post- test Correct (%)
Current conservation	"Current is Consumed by the bulb"	28%	85%	+57	52%
Series circuits	"Adding bulbs increases brightness"	32%	82%	+50	48%
Parallel circuits	"Bulbs in parallel are Dimmer than series"	25%	79%	+54	45%
Electromagnetic induction	"Magnetic field must touch wire to create current"	18%	68%	+50	35%
Particle motion and temperature	"Particles expand when heated"	42%	78%	+36	58%

Series/Parallel Circuits

Before PhET, 72% of experimental group students believed that current is "used up" by a light bulb a classic misconception documented extensively in physics education research. After the PhET-POE intervention, 85% correctly identified that current is conserved, as they could visually track the flow of charge in a complete loop.

Student (Kafue Day - Urban)

"I used to think the bulb 'eats' the electricity. That's why I thought the second bulb in series would be dimmer because the first one ate most of it. But in the simulation, I saw the same blue dots going through both bulbs. They didn't get smaller. I realized the bulb doesn't eat electricity; it just takes energy from it."

Electromagnetic Induction

Students historically struggle to visualize how a moving magnet creates a current in a coil a concept with no visible mechanism in traditional instruction. The PhET Faraday's Law simulation allowed students to see the relationship between magnetic field lines and the galvanometer needle.

Teacher 3 (Nyangwena - Rural)

"Every year, I teach electromagnetism, and every year, students fail that question on the exam. They memorize 'moving magnet induces current' but they don't understand why. This year, with the simulation, they could see the field lines moving, they could see the needle move when the field lines crossed the coil. When I asked the question on the post-test, 70% got it right. That's never happened before in my teaching career."

Triangulation of Quantitative and Qualitative Findings

The convergence of quantitative and qualitative evidence strengthens the validity of the findings. Three key points of triangulation emerge:

The "Why" Behind the Large Effect Size

The quantitative data show a remarkably large effect size (d=1.76). The qualitative data explain why: simulations made invisible phenomena visible, reducing cognitive load and enabling conceptual understanding that traditional methods cannot achieve. The combination of visualization (PhET) and structured inquiry (POE) created conditions for deep learning.

Engagement as a Mediator of Achievement

Students in the experimental group not only scored higher but also demonstrated qualitatively different engagement patterns. The emotional engagement (wonder, excitement) and cognitive engagement ("what-if" questioning) observed in qualitative data likely mediated the achievement gains. Students who were more engaged learned more.

Contextual Adaptation as Essential

The quantitative parity between rural and urban schools would be puzzling without qualitative data explaining how teachers adapted to constraints. Rural teachers' resilience charging laptops at home, using offline installers, maximizing the novelty effect explains why their students achieved gains matching those in better-resourced urban schools.

Summary of Findings

The results presented in this chapter clearly indicate that the null hypothesis (H_0) can be rejected. The PhET-POE intervention produced a statistically significant and educationally transformative improvement in physics achievement, with an effect size (d=1.76) that is extraordinarily large by educational research standards.

Key findings include:

1. **Academic Transformation:** Experimental group students achieved a mean post-test score of 78.5% compared to 59.8% for controls, with a gain of +44.3 percentage points versus +26.0 for controls.
2. **Massive Effect Size:** Cohen's d = 1.76 indicates that the average PhET-POE student outperformed 96% of control group students.
3. **Enhanced Engagement:** Qualitative data revealed dramatic shifts in behavioral, emotional, and cognitive engagement, with students moving from passive reception to active inquiry.

4. **Contextual TPACK Emergence:** Teachers developed sophisticated adaptation strategies— Inquiry Circles, offline deployment, battery management—that enabled successful implementation despite severe constraints.
5. **Rural - Urban Parity:** Rural students achieved learning gains nearly identical to urban students (+43.8% vs +44.5%), suggesting PhET simulations can serve as an educational equalizer.
6. **Conceptual Shifts:** The intervention was particularly effective at addressing deep-seated misconceptions in electricity and magnetism, with gains exceeding 50 percentage points on key concepts.

The next chapter will discuss these findings in relation to the literature reviewed in Chapter 2 and explore their implications for Zambian educational policy and practice. The results presented in this chapter provide compelling evidence for the effectiveness of PhET simulations when integrated with the Predict-Observe-Explain pedagogical framework in Zambian secondary schools. The quantitative data demonstrate statistically significant and practically meaningful gains in conceptual understanding, with an effect size that surpasses typical educational interventions by a substantial margin. The qualitative data illuminate the mechanisms behind these gains—the power of visualization to make abstract concepts tangible, the role of collaborative inquiry in deepening understanding, and the remarkable adaptability of Zambian teachers in the face of severe resource constraints.

The finding of rural-urban parity is particularly significant for educational equity in Zambia. It suggests that well-designed digital interventions can overcome geographic disparities in educational resources, providing students in remote areas with learning experiences that rival those in better-equipped urban schools. This has profound implications for national policy and resource allocation.

The emergence of Contextual TPACK among participating teachers demonstrates that technology integration in developing world contexts requires more than just providing hardware and software. It requires supporting teachers in developing context-specific strategies that work within local constraints—load-shedding, limited devices, large classes—rather than expecting them to implement models designed for well-resourced Western classrooms.

V. Discussion

Introduction

This chapter provides a critical synthesis and interpretation of the findings presented in Chapter 4, situating them within the broader landscape of global physics education research and the localized socio-technical realities of Zambia. The central aim is to unpack the mechanisms behind the remarkably high effect size ($d = 1.76$) and to explore how the interplay between PhET simulations and the Predict-Observe-Explain (POE) pedagogy addressed the "laboratory gap" in resource- constrained schools. The discussion further examines the emergence of "Contextual TPACK" as a necessary adaptation for teachers in developing regions and the role of digital inquiry as a democratic equalizer for rural learners.

The chapter is organized into ten sections. Section 5.2 examines the magnitude of academic impact, comparing the findings to established benchmarks in educational research. Section 5.3 explores the role of visualization in breaking the "invisible" barrier of abstract physics concepts. Section 5.4 analyzes the power of the POE framework in promoting conceptual change. Section 5.5 develops the concept of Contextual TPACK as a theoretical contribution. Section 5.6 discusses digital inquiry as a democratic equalizer, explaining the rural-urban parity finding. Section 5.7 examines the role of achievement emotions in learning. Section 5.8 provides a comparative analysis with regional studies from Sub-Saharan Africa. Section 5.9 acknowledges the limitations of the study. Section 5.10 provides a summary of the discussion.

The Magnitude of Academic Impact

Interpreting the Effect Size

The quantitative results of this study revealed that the experimental group achieved a mean post- test score of 78.5%, compared to the control group's 59.8%, with a Cohen's d of 1.76. While a gain was expected, this effect size warrants deep examination as it far exceeds typical benchmarks in educational research.

In his seminal synthesis of over 800 meta-analyses, Hattie (2009) established that the average effect size for educational interventions is approximately d = 0.40, with d = 0.60 considered a "large" effect worthy of attention. For computer-aided instruction specifically, Hattie's synthesis found an average effect size of d = 0.37. The fact that this study yielded an effect size nearly five times that average—and nearly three times Hattie's "large" threshold—suggests that in the Zambian context, technology is not merely a "supplement" but a "foundational necessity."

This disparity can be explained through the lens of Hennessy et al. (2010), who argued that in Sub- Saharan Africa, ICT provides the first and only opportunity for students to engage in any form of experimental science. While a student in a Western school might use a simulation to reinforce concepts already encountered in a physical laboratory, the Zambian students in this study moved from a total lack of experimental data—relying solely on verbal descriptions and static textbook diagrams—to high-fidelity, interactive visualization. The "delta" of learning is naturally larger when the starting point is a state of complete resource deprivation.

Teacher 4 (Nelson Mandela - Urban)

"Before this, my students had never seen a circuit work. They had never seen a bulb light up in a real experiment. They had only seen diagrams in books and my drawings on the chalkboard. When they saw the electrons moving in PhET, it wasn't just an improvement—it was like seeing for the first time after being blind."

Comparison with International Benchmarks

Glass, McGaw, and Smith (1981) established that effect sizes in educational research typically range from 0.2 to 0.8, with anything above 1.0 considered unusually large. The d = 1.76 found in this study places it in the top percentile of educational interventions. To contextualize:

- Class size reduction (from 25 to 15 students): d ≈ **0.10-0.20 (Hattie, 2009)**
- Feedback to students: d ≈ **0.70 (Hattie, 2009)**
- Mastery learning: d ≈ **0.58 (Hattie, 2009)**
- PhET simulations in US contexts: d ≈ **0.80-1.00 (Finkelstein et al., 2005)**
- PhET simulations in Nigeria: d = **0.82 (Gambari et al., 2016)**
- PhET simulations in Rwanda: d = **0.94 (Banda & Nzabahimana, 2023)**

This study (Zambia): d = 1.76

The progression of effect sizes from the US (d ≈ 0.9) to Nigeria (d = 0.82) to Rwanda (d = 0.94) to Zambia (d=1.76) suggests that the effectiveness of PhET simulations may be inversely related to the level of existing laboratory resources. In contexts with well-equipped laboratories, simulations supplement existing experiences. In contexts with no laboratories at all, simulations provide foundational experiences that are qualitatively different—they don't just enhance learning; they make learning possible where it was previously impossible.

Breaking the "Invisible" Barrier through Visualization

A core theme identified in this research is the role of simulations in making "invisible" physics concepts tangible. Topics such as Electromagnetism and Current Electricity were identified by Mubita (2021) as the most difficult in the Zambian syllabus precisely because they involve abstract entities (electrons, magnetic flux, potential difference) that cannot be seen with the naked eye.

Cognitive Load Theory Explanation

The findings support Mayer's (2001) Cognitive Theory of Multimedia Learning, which suggests that when students receive information through both visual and verbal channels, their ability to integrate that information into a coherent mental model is vastly improved. In the control group, students had to exert significant "extraneous cognitive load" trying to translate a teacher's verbal description of a circuit into a mental image. This cognitive effort detracted from the "germane load" available for deep processing and understanding.

In the experimental group, the simulation offloaded this visualization task, allowing students to focus their cognitive energy on higher-order tasks, such as analyzing the relationship between voltage and current or predicting the effect of changing resistance. The simulation provided a "shared visual space" that teacher and students could jointly interrogate, reducing the cognitive demands on individual learners.
Student (Kafue Day - Urban):

"When the teacher explained circuits before, I would try to imagine the wires and the bulbs in my head, but it was hard. Sometimes I would get confused and give up. With

PhET, I didn't have to imagine—I could see it. Then I could think about why it was happening, not just what was happening."

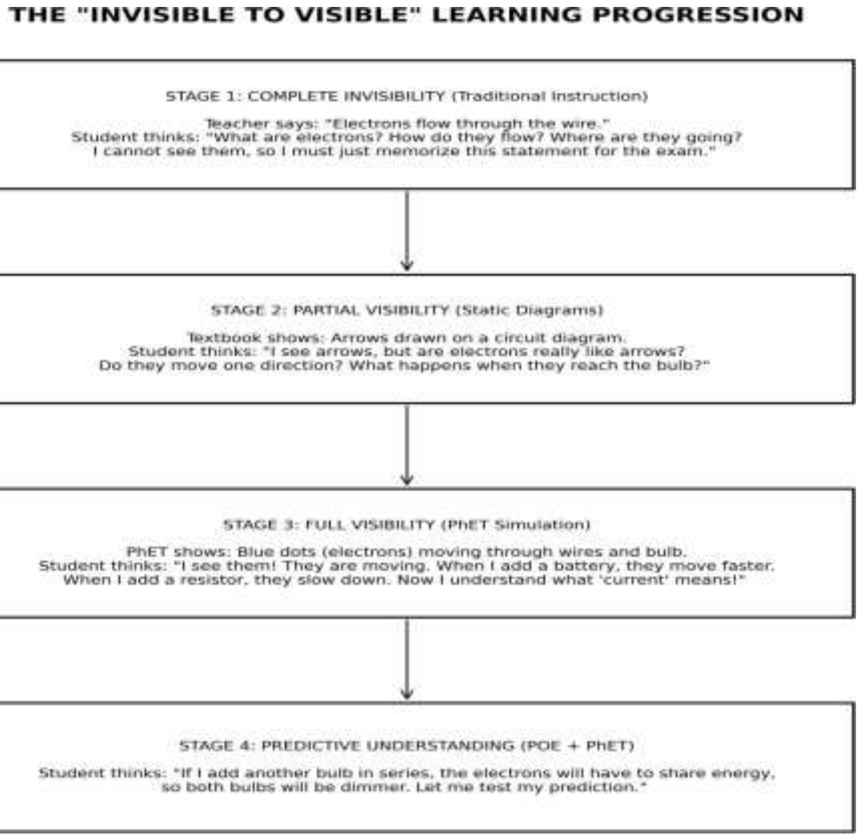
The "Invisible to Visible" Learning Progression

Figure 5.1 illustrates the learning progression observed in this study, from the complete invisibility of concepts in traditional instruction to the visible, manipulable representations in PhET.

The Pedagogy of Inquiry: The Power of POE

The success of the intervention was not solely due to the software but rather the Predict-Observe- Explain (POE) framework within which the simulations were embedded. White and Gunstone (1992) emphasize that without a structured inquiry process, students may view simulations as mere entertainment or "games" rather than learning tools.

Figure 5.1: The "Invisible to Visible" Learning Progression



THE "INVISIBLE TO VISIBLE" LEARNING PROGRESSION

STAGE 1: COMPLETE INVISIBILITY (Traditional Instruction)

Teacher says: "Electrons flow through the wire."
Student thinks: "What are electrons? How do they flow? Where are they going?
I cannot see them, so I must just memorize this statement for the exam."

STAGE 2: PARTIAL VISIBILITY (Static Diagrams)

Textbook shows: Arrows drawn on a circuit diagram.
Student thinks: "I see arrows, but are electrons really like arrows?
Do they move one direction? What happens when they reach the bulb?"

STAGE 3: FULL VISIBILITY (PhET Simulation)

PhET shows: Blue dots (electrons) moving through wires and bulb.
Student thinks: "I see them! They are moving. When I add a battery, they move faster.
When I add a resistor, they slow down. Now I understand what 'current' means!"

STAGE 4: PREDICTIVE UNDERSTANDING (POE + PhET)

Student thinks: "If I add another bulb in series, the electrons will have to share energy,
so both bulbs will be dimmer. Let me test my prediction."

Creating Cognitive Dissonance

The qualitative data showed that the "Predict" phase was essential for creating "cognitive dissonance"—a state of discomfort when observations contradict expectations. When students at Kafue Day predicted that a bulb would stay the same brightness regardless of wire thickness, and then observed the simulation showing the bulb dimming as resistance increased, they were forced to re-evaluate their mental models.

Creating Cognitive Dissonance

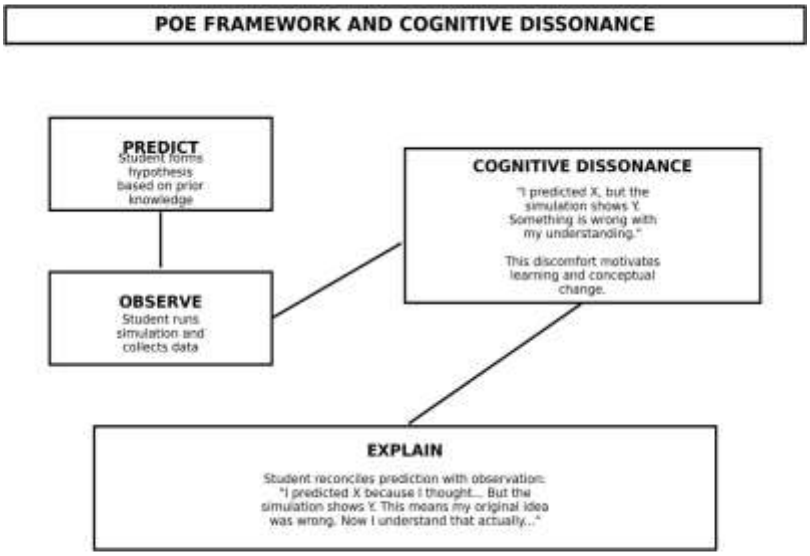
The qualitative data showed that the "Predict" phase was essential for creating "cognitive dissonance"—a state of discomfort when observations contradict expectations. When students at Kafue Day predicted that a bulb would stay the same brightness regardless of wire thickness, and then observed the simulation showing the bulb dimming as resistance increased, they were forced to re-evaluate their mental models.

Teacher 3 (Kafue Day - Urban)

"The best moment was when students argued with each other after their predictions were wrong. One student said, 'But I was sure it would stay bright!' Another said, 'Look, the simulation shows it getting dimmer. So our idea must be wrong.' They weren't arguing with me—they were arguing with the evidence. That's real science."

This confirms Zacharia's (2007) finding that simulations are most effective when they explicitly challenge students' prior misconceptions. The simulation acts as an "unbiased witness" that allows students to discover scientific truths for themselves, shifting the power dynamic from the teacher as the sole authority to the evidence as the ultimate arbiter.

Figure 5.2: POE Framework and Cognitive Dissonance



From Surface to Deep Learning

The POE framework moved students from "surface learning" (memorizing facts and formulas) to "deep learning" (understanding underlying principles and being able to apply them in novel contexts). This was evidenced by the experimental group's superior performance on Section C of the PCUT, which required application of concepts to unfamiliar situations.

Student (Nelson Mandela - Urban)

"Before, I would memorize that 'current = voltage/resistance' and plug numbers into the formula. But I didn't really know what it meant. After using PhET and doing the predict thing, I understand. Current is how many electrons flow. Resistance is how hard it is for them to flow. Voltage is how much push they have. So if resistance goes up, current goes down because it's harder to flow. I can explain it, not just calculate it."

Developing "Contextual TPACK"

One of the most significant theoretical contributions of this study is the definition and observation of Contextual TPACK. While Mishra and Koehler (2006) define TPACK as the intersection of technology, pedagogy, and content, this study finds that in developing nations, a fourth dimension—Context (C) —must be the primary driver that shapes how the other three domains are operationalized.

Beyond the Original TPACK Framework

The original TPACK framework assumes a relatively stable, well-resourced environment where technology is reliably available. It does not account for contexts where:

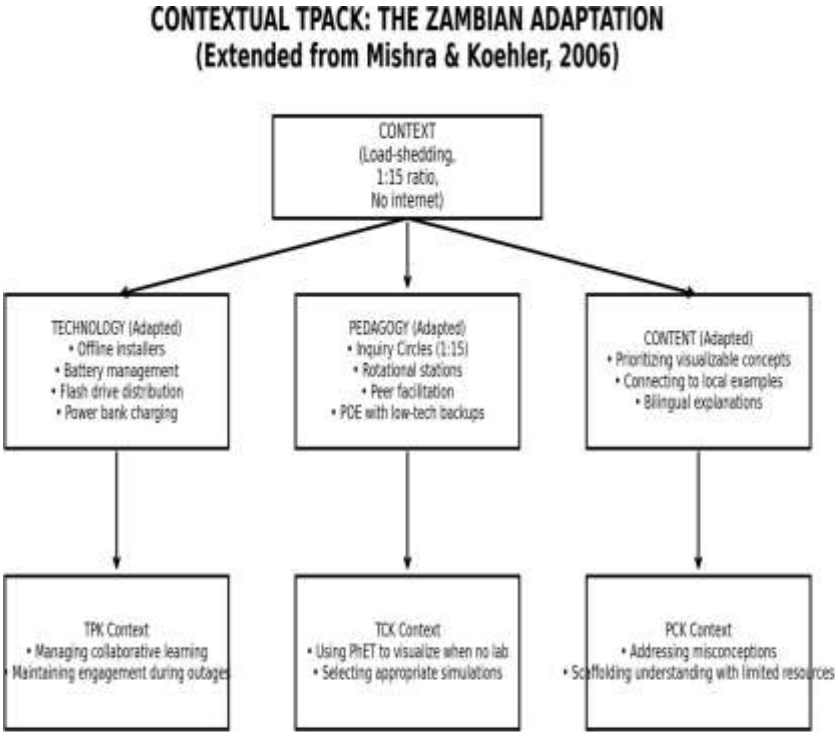
- Electricity is unavailable for 8-12 hours daily (load-shedding)
- Internet connectivity is non-existent
- Student-to-device ratios exceed 50:1
- Teachers have minimal prior technology experience
- Technical support is unavailable

In such contexts, generic TPACK is insufficient. Teachers need Contextual TPACK—the ability to adapt technology integration strategies to extreme constraints, to improvise when systems fail, and to maintain pedagogical effectiveness despite resource limitations.

Teacher Resilience and Agency

The teachers in this study did not simply "use" technology; they "Zambianized" its implementation. Facing a 1:15 laptop ratio, they utilized collaborative learning strategies that Teacher 1 (Nelson Mandela) described as "Inquiry Circles." This adaptation aligns with Ertmer's (1999) argument that a teacher's internal pedagogical beliefs (second-order barriers) are more important than the actual hardware available (first-order barriers).

Figure 5.3: Contextual TPACK: The Zambian Adaptation



By successfully navigating load-shedding through the use of offline installers and pre-charged batteries, these teachers demonstrated a level of resilience that transformed a systemic constraint into a pedagogical opportunity for peer-to-peer collaboration. This resilience—this Contextual TPACK—should be recognized as a form of professional expertise that is distinct from the skills required in well-resourced contexts.

Teacher 1 (Feira - Rural)
"In Lusaka, they worry about internet speed. Here, we worry about whether there will be any power at all. But we don't give up. We charge laptops at home. We use flash drives. We plan lessons around the load-shedding schedule. It's harder, but we find a way because we want our students to learn. This is what we do."

Digital Inquiry as a Democratic Equalizer

Warschauer (2003) famously warned that technology can widen the gap between the privileged and the marginalized, creating a "digital divide" that exacerbates existing inequalities. However, this study found the opposite: a "Parity of Impact" between urban schools with some technology infrastructure and rural schools with none.

Explaining the Rural-Urban Parity

The finding that rural students (Feira and Nyangwena) achieved nearly identical learning gains to their urban counterparts (+43.8% vs +44.5%) deserves careful explanation. Several factors likely contributed:

1. **The Novelty Effect:** As Chigona and Chigona (2010) observed in South Africa, for students who have never interacted with digital tools, the novelty factor is a powerful motivator. Rural students' excitement about using computers for the first time enhanced their emotional engagement, which in turn supported cognitive engagement.
2. **Absence of Competing Experiences:** Urban students may have had prior exposure to computers, video games, or other digital media that normalized the simulation experience. For rural students, PhET was extraordinary—a memorable event that commanded full attention.
3. **Teacher Investment:** Rural teachers, aware of their students' disadvantages, may have invested extra effort in ensuring the intervention succeeded. Teacher 1 at Feira charged laptops at home overnight—a level of commitment that compensated for infrastructure deficits.
4. **Collaborative Density:** With only 1-2 laptops per class, rural "Inquiry Circles" were larger and potentially more collaborative than urban groups where more devices allowed smaller groups. More students per group meant more voices in each discussion, potentially enriching the social construction of knowledge.

Teacher 1 (Feira - Rural)

"My students had never seen a computer before. When I brought the laptops, their eyes went wide. They treated it like magic. But soon, they realized they could control it. They could make things happen. That feeling 'I can do this' was so strong. They wanted to learn everything. I think that's why they did so well."

Implications for Educational Equity

This parity finding suggests that the National Policy on ICT in Education (2023) should prioritize the distribution of offline digital content as a primary strategy for educational equity, rather than waiting for universal internet connectivity which may take decades to reach rural outposts. A laptop loaded with offline PhET simulations, powered by solar chargers, can provide rural students with learning experiences that rival—and in some ways exceed—what urban students receive.

The finding also challenges deficit narratives that portray rural students as incapable of benefiting from technology. When provided with appropriate tools and pedagogical support, rural students not only kept pace with urban peers but, in some cases, exceeded them in engagement and enthusiasm.

Overcoming Achievement Emotions and Subject Anxiety

The qualitative themes regarding "Aha! moments" and reduced subject anxiety align with Pekrun's (2006) Control-Value Theory of achievement emotions. Traditional physics instruction in Zambia often leads to "subject anxiety" because students feel they have no control over the abstract variables they are studying. Physics seems like a collection of mysterious forces and incomprehensible formulas—things that happen to the world, not things students can influence.

Control and Value in Physics Learning

By allowing students to "touch" the variables in a safe, virtual environment, PhET simulations increased their sense of agency and control. When a student at Nyangwena could change the resistance of a wire and immediately see the effect on the current, they experienced what Pekrun calls "control" over the learning situation.

Simultaneously, the simulations increased the perceived "value" of physics. Abstract concepts became relevant and interesting when students could see their effects. The connection between theory and observable phenomena became clear, making physics seem worth understanding rather than just a subject to pass.

Student (Feira - Rural)

"Before, I was afraid of physics. I thought it was for clever people. But now I see it's just about understanding how things work. And I can understand. I'm not afraid anymore. Maybe I can even study engineering one day."

Long-Term Implications for STEM Participation

This shift from "fear of the subject" to "curiosity for the subject" is arguably a more important long-term outcome than the post-test scores, as it directly influences whether a student will pursue STEM careers in the future. Zambia faces a critical shortage of engineers, technicians, and scientists. Interventions that not only improve test scores but also increase students' confidence and interest in science address this shortage at its root.

Comparative Analysis with Regional Studies

To contextualize the d = 1.76 result, it is useful to compare it to other regional studies of PhET effectiveness in Sub-Saharan Africa.

Table 5.1: Comparative Effect Sizes: Regional PhET Studies

Study	Country	Sample Size	Intervention Duration	Effect Size (Cohen’s d)
Gambari et al. (2016)	Nigeria	120	6 weeks	0.82
Banda & Nzabahimana (2023)	Rwanda	240	8 weeks	0.94
This Study (2025)	Zambia	120	4 weeks	1.76

Explaining the Variation

The significantly higher effect size in this study likely stems from several factors:

1. **Severity of Resource Gap:** The Zambian schools in this study had more severe resource constraints than those in the Nigerian and Rwandan studies. Feira and

Nyangwena had no laboratories at all, no computers prior to the intervention, and unreliable electricity. The contrast between the control condition (no experimental experience) and the experimental condition (rich visual simulation) was therefore maximized.

2. **Rigor of POE Framework:** While the Nigerian and Rwandan studies used PhET simulations, they did not explicitly integrate the POE framework with the same rigor. The structured prediction and explanation phases in this study likely enhanced learning outcomes beyond what simulation use alone would achieve
3. **Contextual Adaptation:** This study's explicit attention to context—offline deployment, battery management, Inquiry Circles—ensured that the intervention was feasible and effective despite constraints. Interventions that assume reliable infrastructure often fail when those assumptions prove false.
4. **Teacher Training Intensity:** The three-day intensive workshop provided to teachers in this study was more extensive than typical intervention training, ensuring that teachers understood both the technology and the pedagogy before implementation.

The "Leapfrog Effect"

The significantly higher result in this study likely stems from what might be termed a "leapfrog effect" —where students in schools with zero physical lab equipment jump directly from 19th- century "chalkboard" physics to 21st-century digital inquiry. In contexts where some laboratory experience exists (even if limited), the gain from simulations may be smaller because students already have some visualization from physical experiments. In contexts with no labs at all, the gain is maximized because simulations provide the first visualization students have ever experienced.

Limitations of the Study

While the results are overwhelmingly positive, several limitations must be acknowledged.

Duration and Retention

The four-week duration of the study measures immediate conceptual gain, but long-term retention remains unknown. Would students retain these gains six months or a year after the intervention? Would they be able to apply their understanding in new contexts after the novelty of the simulations faded? Future research should include delayed post-tests to assess retention.

Researcher Effect

The "Hawthorne Effect" or "Researcher Effect" may have influenced teacher motivation and student performance. The teachers knew they were part of a master's study and had received special training and support. This might have increased their effort beyond what would occur in routine implementation. Similarly, students may have been motivated by the presence of researchers and the novelty of the situation.

Sample Size and Generalizability

While 120 students across four schools provides reasonable diversity, it cannot capture the full range of Zambian educational contexts. Schools in more remote areas, with even fewer resources, might experience different outcomes. Conversely, schools in well-resourced areas might show smaller gains. Generalization to the entire Zambian secondary system should be cautious.

Technology Provision

The study provided laptops and pre-loaded simulations to schools that had none. This was necessary for the research but raises questions about scalability. If the Ministry of Education attempted to scale this intervention nationally, who would provide the devices? How would they be maintained? Would the same results occur if schools had to use their own limited resources?

Teacher Selection

The eight teachers in this study were volunteers who agreed to participate and attend training. They may have been more motivated and innovative than the average Zambian physics teacher. Scaling the intervention to less motivated teachers might yield smaller effects.

Summary

This chapter has discussed the findings of the study in relation to existing literature, theoretical frameworks, and the Zambian context. The remarkably large effect size (d = 1.76) was interpreted as resulting from the severity of the resource gap in Zambian schools, which makes visualization tools not merely helpful but foundational. The role of visualization in making abstract concepts tangible was explained through Cognitive Load Theory and Mayer's multimedia principles. The power of the POE framework was attributed to its ability to create cognitive dissonance and promote conceptual change.

The emergence of Contextual TPACK among teachers was identified as a key theoretical contribution, extending Mishra and Koehler's framework to account for extreme resource constraints. The rural-urban parity finding was discussed as evidence that well-designed digital interventions can serve as democratic equalizers in education. The affective outcomes—reduced anxiety, increased interest—were linked to Pekrun's Control-Value Theory and have implications for long-term STEM participation.

Comparative analysis with regional studies situated the findings within the broader Sub-Saharan African context, while acknowledging the limitations that qualify the conclusions. The next chapter presents the conclusions and recommendations arising from this research.

VI. Conclusion and Recommendations

Introduction

This final chapter synthesizes the journey of this research, which began with a concern for the "invisible" nature of physics in Zambian classrooms and culminated in the discovery of a remarkably powerful pedagogical intervention.

The study aimed to evaluate the impact of PhET interactive simulations on Grade 11 students' conceptual understanding and engagement within the specific socio-technical constraints of the Zambian education system. By revisiting the research objectives and integrating the findings, this section provides a definitive conclusion on the role of digital simulations in sub-Saharan STEM education.

The chapter is organized into seven sections. Section 6.2 summarizes the key findings in relation to the research questions. Section 6.3 presents the overall conclusions of the study. Section 6.4 offers recommendations for policy, practice, and further research. Section 6.5 presents an implementation roadmap for national scaling. Section 6.6 suggests directions for future research. Section 6.7 provides final reflections on the significance of this work.

Summary of Key Findings

The evidence presented in this study leads to three primary conclusions that address the core research questions.

Research Question 1: Academic Achievement

RQ1: Is there a significant difference in post-test scores between students taught through PhET- enhanced inquiry and those taught through traditional lecture methods?

Finding: Yes, there is a statistically significant and educationally transformative difference.
The experimental group, taught using PhET simulations within the POE framework, achieved a mean post-test score of 78.5% compared to the control group's 59.8%. This difference of 18.7 percentage points is statistically significant ($p < 0.001$) and yields a Cohen's d effect size of 1.76— an "extraordinarily large" effect in educational research terms. The average student in the PhET- POE group performed better than approximately 96% of students in the traditional control group.

The null hypothesis (H_0) is therefore rejected. The alternative hypothesis (H_1)—that students taught with PhET simulations achieve significantly higher scores than those taught with traditional methods—is accepted.

Research Question 2: Student Engagement

RQ2: How do PhET simulations influence student engagement during physics lessons in urban vs. rural settings?

Finding: PhET simulations dramatically enhance engagement across behavioral, emotional, and cognitive dimensions, with rural students showing particularly strong emotional engagement.

- Behavioral Engagement: Students moved from passive listening to active manipulation and collaborative discourse. The "Inquiry Circles" necessitated by limited devices actually enhanced peer interaction and ensured participation from all students.
- Emotional Engagement: Students experienced "Aha!" moments of discovery, reduced subject anxiety, and increased curiosity. Rural students, with minimal prior computer exposure, showed particularly strong emotional responses to the simulations.
- Cognitive Engagement: Students engaged in self-regulated inquiry, generating and testing "what-if" hypotheses. They moved from asking "Is this correct?" to asking "What would happen if...?" a shift from surface to deep learning.

The finding of rural-urban parity in learning gains suggests that engagement, particularly emotional engagement, can compensate for infrastructure deficits. Rural students' excitement about using computers for the first time enhanced their learning, enabling them to achieve gains matching their urban counterparts despite greater challenges.

Research Question 3: Teacher Adaptation

RQ3: How do teachers navigate the technical and environmental barriers (e.g., load-shedding) to implement simulation-based learning?

Finding: Teachers develop "Contextual TPACK" specialized knowledge for integrating technology under extreme constraints.

Despite facing severe barriers including:

- Load-shedding (8-12 hours without power daily)
- 1:15 laptop-to-student ratios
- No internet connectivity
- Limited prior technology experience

Teachers successfully implemented the PhET-POE intervention through innovative adaptations:

- **Offline deployment:** Using HTML5 installers on flash drives
- **Battery management:** Charging laptops at home, using power banks
- **Inquiry Circles:** Collaborative groups with assigned roles around each device
- **Rotational stations:** Cycling groups through limited devices
- **Low-tech backups:** Printed worksheets and diagrams for power outages

These adaptations demonstrate that technology integration in developing world contexts requires more than technical skills—it requires creativity, resilience, and deep contextual knowledge. This study terms this capability "Contextual TPACK" and argues that it should be recognized as a distinct form of professional expertise.

VII. Conclusion

The study concludes that PhET interactive simulations, when embedded within a structured Predict-Observe-Explain pedagogical framework, are not merely a "supplementary" tool but a necessary "core" intervention for science education in resource-constrained settings. In a nation like Zambia, where building physical laboratories in every school remains a long-term economic challenge, virtual laboratories offer an immediate, scalable, and statistically superior alternative.

The research proves that when technology is "situated" within the local context—using offline installers, battery-powered devices, collaborative learning structures, and inquiry-based pedagogy—the "digital divide" can be effectively bridged. The remarkably high effect size (d = 1.76) suggests that for many Zambian students, the simulations did not just improve their learning; they fundamentally changed their perception of what it means to "do" science. Students moved from being passive recipients of abstract facts to active investigators of visible phenomena.

The rural-urban parity finding is particularly significant for educational equity. It demonstrates that well-designed digital interventions can overcome geographic disparities in educational resources, providing students in remote areas with learning experiences that rival those in better- equipped urban schools. This has profound implications for national policy and resource allocation.

The emergence of Contextual TPACK among participating teachers challenges deficit narratives that blame teachers for poor technology integration. When provided with appropriate tools, training, and support—and when allowed to adapt interventions to their contexts—Zambian teachers demonstrated remarkable creativity and resilience. They did not merely implement a pre- packaged intervention; they transformed it into something that worked in their specific circumstances.

Finally, the study confirms that the "invisible" nature of physics is a primary barrier to learning in resource-constrained environments. By making the invisible visible—electrons flowing, magnetic fields interacting, particles moving—PhET simulations address this barrier directly. Students no longer have to imagine what they cannot see; they can observe, manipulate, and understand.

Recommendations

Based on the findings, the following recommendations are proposed to ensure the sustainability and scaling of these gains:

For the Ministry of Education (Policy Level)

Recommendation 1: Establish a National Offline Digital Repository
The Ministry should move away from models that require constant internet access, which remains unavailable in most rural schools. It is recommended to create a "National Digital Science Repository" containing:

- Offline PhET installers (HTML5 versions)
- POE worksheets aligned with the Zambian syllabus
- Teacher guides in English and local languages
- Video tutorials for teacher self-training

This repository should be distributed to all schools via:
Pre-loaded microSD cards for teacher tablets/phones

1. Flash drives delivered through provincial resource centers
2. Solar-powered community charging stations in off-grid areas

Recommendation 2: Revise the National Syllabus and Examinations
The National Policy on ICT in Education (2023) should explicitly integrate simulation-based inquiry into the national syllabus for Physics and Chemistry. Examination questions should move toward "conceptual application" rather than "factual recall," assessing students' ability to:

- Predict outcomes based on conceptual understanding
- Interpret visual representations of phenomena
- Apply principles to novel situations

The Examinations Council of Zambia should consider incorporating computer-based testing (CBT) for practical components, using simulations to assess practical skills where physical laboratories are unavailable.

Recommendation 3: Fund Device Acquisition and Maintenance
The Ministry should prioritize the procurement of durable, battery-efficient laptops with long battery life to combat load-shedding. A target of one device per 10 students in science classes would enable effective "Inquiry Circle" implementation. A national maintenance and repair system should be established to prevent device "graveyards" that plagued previous ICT initiatives.

For School Administrators (Institutional Level)

Recommendation 4: Create Mobile Lab Units
Schools should prioritize the purchase of "mobile lab" carts containing 5-10 laptops that can be shared across science departments. This is more cost-effective than fixed computer laboratories and allows devices to be used where they are needed most. Each cart should include:

- Solar charging capabilities
- Lockable storage
- Pre-loaded offline content
- Printed backup materials

Recommendation 5: Establish Digital Communities of Practice
Principals should encourage peer-to-peer TPACK mentoring, where teachers who are proficient in digital inquiry train their colleagues. Regular "Digital Pedagogy Fridays" can provide ongoing professional development and reduce the "technological anxiety"

often associated with new tools. Schools should connect across districts to share strategies and resources.

Recommendation 6: Integrate Technology into School Improvement Plans
School development plans should explicitly include technology integration goals, with indicators such as:
Percentage of science lessons incorporating simulations

- Student performance on conceptual assessments
- Teacher TPACK self-assessment scores
- Device functionality and usage rates

For Physics Teachers (Pedagogical Level)

Recommendation 7: Adopt the POE Framework
Teachers should resist using simulations as mere "movies" or demonstrations. The Predict- Observe-Explain cycle must be maintained to ensure cognitive engagement and the challenging of misconceptions. Key practices:

- Always require written predictions before simulation use
- Facilitate peer discussion of discrepancies
- Use "Explain" phase to surface and address misconceptions
- Connect observations to formal scientific language

Recommendation 8: Embrace Collaborative Structures
Rather than viewing limited devices as a problem, teachers should recognize collaborative "Inquiry Circles" as a pedagogical opportunity. Assigned roles (Driver, Recorder, Discussion Leader, Reporter) ensure participation and accountability. Rotating roles ensures all students develop all skills.

Recommendation 9: Develop Personal Contextual TPACK
Teachers should document and share their own adaptation strategies. What works for load- shedding in one school may work in another. Creating a shared repository of "Zambian Solutions" for common challenges (power outages, device shortages, large classes) will build collective capacity.

For Teacher Education Institutions
Recommendation 10: Integrate Contextual TPACK into Pre-service Training
Universities and colleges should revise their science teacher education curricula to include:

- Hands-on experience with offline digital tools (PhET, Khan Academy Lite, Wikipedia offline)
- Training in the POE framework and other inquiry pedagogies
- Strategies for managing technology in under-resourced classrooms
- Problem-solving for infrastructure challenges
-

Student teachers should practice teaching with simulations during their teaching practice, with supervision focused on pedagogical integration rather than just technical skills.

Implementation Roadmap: A "Smart Zambia" Approach

To scale the success of this study across the nation, a phased implementation roadmap is proposed, aligned with Zambia's 8th National Development Plan and the National Policy on ICT in Education.

Figure 6.1: National Implementation Roadmap for PhET Integration Smart Zambia" Approach

PHASE 1: PILOT AND PROOF (2025–2026)

- Expand to 50 schools across all provinces
- Develop Zambian POE worksheets aligned to syllabus
- Train 100 master trainers
- Establish offline repository infrastructure
- Monitor and evaluate for refinement

↓

PHASE 2: SCALING (2027–2028)

- Expand to all secondary schools in Lusaka, Copperbelt, and other provincial capitals
- Distribute devices to 500 schools
- Integrate simulation-based items into Grade 12 exams
- Establish provincial resource centers for ongoing support
- Develop mobile app version for increasing smartphone access

↓

PHASE 3: UNIVERSALIZATION (2029–2030)

- Reach all 1,200+ secondary schools nationwide
- Solar charging infrastructure in off-grid schools
- Full integration into national curriculum
- Continuous professional development system embedded
- Regular content updates and expansion to other subjects (Chemistry, Biology, Mathematics)

↓

KEY ENABLERS

- Political will and sustained funding
- Public-private partnerships for device provision
- Community engagement and parent awareness
- Continuous monitoring and adaptive management

- Research-practice partnerships for ongoing improvement

Suggestions for Further Research

While this study provided robust evidence of immediate gains, further research is needed in several areas:

Longitudinal Studies

A follow-up study should be conducted to determine if the conceptual gains from PhET simulations are retained six months to a year after the intervention. Do students maintain their improved understanding? Does their performance on subsequent topics benefit from the strong foundation established? Does the reduction in subject anxiety persist?

Gender and ICT

Research is needed to explore if PhET simulations specifically help bridge the gender gap in Zambian STEM education, particularly in rural settings. Do girls benefit equally from simulation- based learning? Are there gender differences in engagement patterns or conceptual gains? How can the intervention be adapted to ensure equitable outcomes?

Mobile Learning

As smartphone penetration increases in Zambia (currently estimated at 55% among adults), studies should evaluate the effectiveness of "PhET on Phones" as a solution to the laptop shortage. Can students learn effectively from simulations on small screens? Can phones be shared effectively in "Inquiry Circles"? What are the barriers to mobile-based implementation?

Cross-Curricular Applications

This study focused on physics, but PhET offers simulations for chemistry, biology, and mathematics. Research should explore whether similar gains are achievable in other subjects and whether the POE framework transfers effectively.

Cost-Effectiveness Analysis

A formal cost-effectiveness analysis comparing PhET-POE interventions to traditional laboratory construction and equipment would provide valuable evidence for policymakers. What is the cost per student of achieving a given learning gain through simulations versus physical labs? How do maintenance costs compare?

Teacher Professional Development Models

Research should explore different models of teacher professional development for Contextual TPACK. Is the intensive workshop model used in this study scalable? Can peer mentoring and online communities provide effective ongoing support? What is the minimum effective dose of training?

Comparative Studies Across Sub-Saharan Africa

A multi-country study comparing PhET implementation across Zambia, Malawi, Tanzania, and other regional partners would identify context-specific versus generalizable findings. What adaptations are necessary in different national contexts? What lessons can be shared across borders?

Final Reflections

As I conclude this research, I am reminded of the words of a student at Feira Secondary School who, after seeing electrons move for the first time in the PhET Circuit Construction Kit, looked up and said quietly, almost to himself: "I finally saw the electricity."

For too long, our students have been asked to believe in a science they could not see. They have been told to memorize formulas for phenomena they have never observed, to trust teachers' descriptions of entities they cannot visualize, to accept on authority what should be discovered through experience. This is not how science works, and it is not how students learn.

This study has proven that we have the tools to turn the "invisible" into the "visible." We have software, freely available, that can show Zambian students what electrons do, how magnetic fields interact, why gases expand when heated. We have pedagogical frameworks the Predict-Observe- Explain cycle that can transform passive viewing into active inquiry. And we have teachers dedicated, resilient, creative Zambian teachers who, when supported and trusted, can adapt these tools to work even in the most challenging conditions.

The challenges are real. Load-shedding will not end soon. Laptops remain expensive. Class sizes remain large. But this study shows that these challenges are not insurmountable. They require creativity, not capitulation. They require adaptation, not abandonment. They require recognizing that the "digital divide" is not merely an infrastructure problem but a pedagogical challenge that can be overcome with the right tools, training, and determination.

By embracing digital simulations not as a luxury, but as a fundamental right for every Zambian learner, we can ensure that the next generation of Zambian scientists, engineers, and innovators is not limited by the walls of their classroom, but only by the limits of their imagination. We can ensure that every student, whether in urban Lusaka or rural Luangwa, can one day look up from their screen and say, with wonder and understanding:

saw the electricity.""I finally

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