# The relationship between teachers' pedagogical content knowledge about electrostatics and learners' performance

by

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A thesis submitted in partial fulfilment of the requirements for the degree

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Supervisor: Prof. Estelle Gaigher

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## Declaration

I, Ernest Nkosingiphile Mazibe, student number: 29653054, declare that this Doctoral thesis entitled: "**The relationship between teachers' pedagogical content knowledge about electrostatics and learners' performance**" which I hereby submit for the degree Philosophiae Doctor is my own work. I further declare that this thesis has never been submitted for examination at this or any other institution before. Work from other sources used in this study has been acknowledged accordingly.

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## Dedication

I dedicate this piece of work to:

- My mom, Zulmira ‘Zuleka’ Mazibe. You have raised your children with love and made us see the value of education. All the sacrifices that you have made to see me go all the way until this point did not go unnoticed.
- My father, Antony Zunguza, and my son, Nhlakanipho Umusa Mazibe. This is for all of us.

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## Abstract

This study investigated the relationship between teachers' pedagogical content knowledge (PCK) about electrostatics and learners' performance in the topic. Two in-service and two pre-service physical science teachers, together with their learners, agreed to participate in the study. The PCK of the teachers was viewed as two manifestations; the personal PCK, which is static in nature and the enacted PCK, which is dynamic. A content representation (CoRe) tool and lesson plans were used to collect data that reflected the personal PCK of the teachers. The data for the enacted PCK was collected using classroom observations, and video stimulated recall (VSR) interviews. A topic specific PCK model was adopted as the framework for this study. The model asserts that specific content is transformed for instruction through five components, namely; learners' prior knowledge, curricular saliency, what is difficult to teach, representations including analogies, and conceptual teaching strategies. Guided by the model, I developed two rubrics to assess and quantify the quality of the teachers' personal and enacted PCK on a four-point scale. Learners, on the other hand, wrote a test developed specifically for this study which explored their performance in the fundamental concepts chosen for this study. The performance of the learners was then related to the personal and the enacted PCK of the teachers separately.

The results revealed that the personal and the enacted PCK of the teachers, as well as the performance of the learners, varied across fundamental concepts of electrostatics. The variations in the personal and enacted PCK provided empirical evidence that supports the notion that PCK has a concept specific nature. The results also showed that the performance of the learners was better related to the enacted PCK of the teachers compared to the personal PCK. These results imply that it is important to make teaching practice the centre of pre-service teacher education given the direct impact of enacted PCK on learning. Furthermore, exploring PCK at concept level reveals the strengths and weaknesses of the concepts. As such, pre-service teacher education and in-service teacher professional development may be tailored in a manner that addresses the concepts that require intervention.

**Key words**: concept-specific pedagogical content knowledge, content representations, electrostatics, learners’ performance.

## Language editor's disclaimer

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**TO WHOM IT MAY CONCERN**

The dissertation titled "The relationship between teachers' pedagogical content knowledge about electrostatics and learners' performance" by Ernest Nkosingiphile Mazibe has been proofread and edited for language by me.

I verify that it is ready for publication or public viewing in respect of language and style and it has been formatted as per the prescribed style of the institution.

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Kind regards

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**List of abbreviations**

| | |
|---|---|
| BEd | Bachelor of Education. |
| CAPS | Curriculum and Assessment Policy Statement. |
| CDE | Centre for Development and Enterprise. |
| CK | Content knowledge. |
| CKT-M | Content knowledge for teaching mathematics. |
| CoRe | Content representation. |
| DoBE | Department of Basic Education. |
| IEA | International Association for the Evaluation of Educational Achievement. |
| LTSM | Learning and teaching support materials. |
| NCS | National Curriculum Statement. |
| NSC | National Senior Certificate. |
| TIMSS | Trends in International Mathematics and Science Studies. |
| TPKB | Teacher professional knowledge bases. |
| TPK&S | Teacher professional knowledge and skill. |
| TSPCK | Topic specific pedagogical content knowledge. |
| TSPK | Topic specific professional knowledge. |
| PCK | Pedagogical content knowledge. |
| PGCE | Post-graduate certificate in education. |
| RCM | Refined consensus model. |
| UNESCO | United Nations Educational, Scientific and Cultural Organisation. |
| VSR | Video stimulated recall. |

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# 1. CHAPTER ONE: ORIENTATION AND STUDY BACKGROUND

## 1.1 INTRODUCTION

This chapter introduces a research study that investigates the relationship between teachers' pedagogical content knowledge (PCK) and learners' outcomes in the topic of electrostatics. In this chapter, I will provide a brief description of PCK as it is the foundation on which this study is based. I will then describe the South African educational context by outlining the nature of science teaching and learning in the country. Concerning the topic of electrostatics, I will describe its scope in the curriculum as well as the trends in learners' performance in the topic both locally and internationally. I will then discuss the research problem to be addressed, followed by the rationale for this study. In addition, I will present the formulated research questions as well as the assumptions upon which this study is based. Finally, I will provide a summary that describes the chapter layout of the thesis.

## 1.2 BACKGROUND: PEDAGOGICAL CONTENT KNOWLEDGE

PCK was introduced into science education by Shulman (1986, p. 6) as a "missing paradigm" following the absence of focus on subject content in research about teachers' knowledge at the time. He described it as follows:

> *Pedagogical content knowledge include, for the most regularly taught topics in one's subject area, the most useful forms of representations of those ideas, the most powerful analogies, illustrations, examples, explanations and demonstrations – in a word, the ways of presenting and formulating the subject that makes it comprehensible to others.* (Shulman, 1986, p. 9)

His argument was that PCK refers to the knowledge of teaching emerging from the amalgam of content and pedagogy (Shulman, 1987). PCK, therefore, lies at the centre of effective teaching (Cochran, DeRuiter & King, 1991) and is considered to be unique, personal and private to individual teachers (Hashweh, 2005). Furthermore, PCK sets teachers apart from individuals that are mere subject specialists (Shulman, 1987). The knowledge of a physics subject specialist, for example, is predominantly structured from a research perspective and is used as the basis of the acquisition of new physics knowledge (Cochran et al., 1991). Thus when required to teach, a subject specialist who has no teaching background would probably rely on the transmission of raw content to learners, an approach which hinders effective learning (Mizzi, 2013). According to Shulman (1987), the following is expected from teachers:

> *[Teachers are expected to shift] from being able to comprehend subject matter for themselves, to becoming able to elucidate subject matter in new ways, reorganise and partition it, clothe it in activities and emotions, in metaphors and exercises, and in examples and demonstrations, so that it can be grasped by students.* (Shulman, 1987, p. 13)

Since its inception in education, PCK has attracted the attention of researchers who adopted and adapted it to suit their studies. In the earlier years of PCK research, researchers predominantly focused on defining the construct by identifying components that shape PCK. Because the researchers were working independently, they conceptualised PCK differently and identified different components that shape the construct. These components included content knowledge, general pedagogical knowledge, knowledge of context, knowledge of learner thinking, knowledge of instructional strategies, knowledge of representations, knowledge of the curriculum, knowledge of assessment and knowledge of educational ends. Furthermore, the components were consolidated into models that describe PCK (Gess-Newsome, 1999, Grossman, 1990; Magnusson, Krajcik & Borko, 1999; Mavhunga & Rollnick, 2013; Rollnick, Bennett, Rhemtula, Dharsey, & Ndlovu, 2008). Although the knowledge bases in these models involve different components, there is a consensus that the knowledge of learners' understanding, as well as instructional strategies and representations, are the foundations of PCK (Shulman, 1987). Furthermore, there is consensus that the quality of PCK extends beyond teachers' competence in the separate components, for example the knowledge of teaching strategies. PCK is also reflected by the coherent interactions of the components that produce powerful classroom instructions (Abell, 2008; Magnusson et al., 1999).

Another major development in the understanding of PCK was the introduction of a taxonomy that describes levels of teacher knowledge by Veal and MaKinster (1999). They identified three levels of PCK, namely; general PCK, domain-specific PCK and topic-specific PCK, which represent the grain sizes of the construct. These levels distinguish between the knowledge needed for teaching a subject, for example science, a domain, for instance, physics, and a topic, such as electrostatics. In recent times, PCK researchers have recognised the concept-specific nature of teachers' PCK (Carlson & Daelher, 2019; Smith & Banilower, 2015). The acknowledgement of the concept-specific nature of teacher knowledge emerged as one of the products of two PCK summits held in 2012 and 2016.

The PCK summits were necessitated by the discrepancies in previous PCK research, particularly the conceptualisations and the models of the construct that made it difficult to compare empirical results across contexts and topics (Carlson & Daehler, 2019). As such, the summits allowed renowned researchers to share their conceptualisation of PCK which resulted in the consensus model (Gess-Newsome, 2015) and the refined consensus model (RCM) of PCK (Carlson & Daehler, 2019). These and other outcomes of the summits will be discussed in detail in the next chapter. However, it is worth mentioning that the theoretical connection between teachers' PCK and learners' outcomes has been described in the models despite the paucity of research evidence with regards to the effect of PCK on learning.

## 1.3 CONTEXT: SCIENCE TEACHING AND LEARNING IN SOUTH AFRICA

### 1.3.1 Learners' performance in science

According to the United Nations Educational, Scientific and Cultural Organisation (UNESCO, 2017), education in general and science education, in particular, are the drivers of social and economic development. It is unfortunate however, that learners worldwide find it difficult to understand science concepts, particularly those of physics (Thomas, 2013). South African learners are no exception to this global challenge, as indicated by their continuous poor performance in local and international science assessments. Locally, diagnostic reports from the Department of Basic Education (DoBE), based on the Grade 12 final examination results, have repeatedly shown that the majority of learners perform poorly in physical sciences. According to the South African National Senior Certificate (NSC), which was introduced in 2008, learners are only required to obtain 30 % to pass physical sciences (DBE, 2003; DoBE, 2011). However, the annual performance in physical sciences has been poor, with a significant number of learners failing to obtain at least 30% to pass the subject (See Table 1.1).

*Table 1.1: Grade 12 learners' performance in physical science since 2008*

| Curriculum | Year | Percentage of learners that failed (obtained below 30%) | Percentage of learners that passed (obtained above 30%) | Percentage of learners that obtained more than 40% |
|---|---|---|---|---|
| National Curriculum Statement (NCS). | 2008 | 45.1 % | 54.9 % | 28.8 % |
| | 2009 | 63.2 % | 36.8 % | 20.6 % |
| | 2010 | 52.2 % | 47.8 % | 29.7 % |
| | 2011 | 46.6 % | 53.4 % | 33.8 % |
| | 2012 | 38.7 % | 61.3 % | 39.1 % |
| Curriculum and Assessment Policy Statement (CAPS). | 2013 | 32.6 % | 67.4 % | 42.7 % |
| | 2014 | 38.5 % | 61.5% | 36.9 % |
| | 2015 | 41.4 % | 58.6 % | 36.1 % |
| | 2016 | 38.0 % | 62.0 % | 39.5% |
| | 2017 | 34.9 % | 65.1 % | 42.2 % |
| | 2018 | 25.8 % | 74.2 % | 48.7 % |

South African learners have also performed poorly in comparison to learners from other nations as reported in various international comparative studies. In my discussion of the international comparisons, I specifically refer to the reports from the International Association for the Evaluation of Educational Achievement (IEA). The IEA monitors Trends in International Mathematics and Science Studies (TIMSS) every four years by administering tests to Grade 4 and 8 learners from various nations participating at free will. According to the TIMSS results, South African learners have been performing poorly in the assessments, obtaining scores that are significantly below international averages (Cho, Scherman & Gaigher, 2012; Howie & Plomp, 2006; Reddy, 2006). Some local journalists even believed that the Department of Basic Education (DoBE) in South Africa withdrew from participating in the 2007 study because the country was previously ranked the lowest in 1999 and 2003 (Govender, 2007). However, South Africa again participated in the 2011 and the 2015 edition of the assessments. Table 1.2, adapted from Kazeni (2012) shows the performance of South African learners in different science content areas as well as international averages as reported in TIMSS. The results from the 1995 study were reported as average percentages, whereas the other studies were reported as average scores.

*Table 1.2: South Africa's achievement in TIMSS since 1995.*

| Year | Global average scores | South Africa's scores per science content area | | | | |
|---|---|---|---|---|---|---|
| | | Physics | Chemistry | Life Sciences | Earth Sciences | Environmental Sciences |
| 1995*[1] | 56% | 27% | 26% | 27% | 26% | 27% |
| 1999*[2] | 488 | 308 | 350 | 289 | 348 | 350 |
| 2003*[2] | 474 | 244 | 285 | 250 | 247 | 261 |
| 2011*[2] | 500 | 351 | 336 | 318 | 294 | - |
| 2015*[2] | 500 | 359 | 369 | 356 | 330 | - |

*[1] Results reported as average percentages. *[2] results reported as average scale scores

### 1.3.2 Science teaching in South Africa

The South African education system has been described as "struggling" by the Centre for Development and Enterprise (CDE), which is an organisation that provides research guided policy advice on critical national issues. The first critical issue pertinent to this study is the fact that the education system does not prepare the majority of learners for tertiary studies and the world of work, particularly in science-related fields (CDE, 2017). The second critical issue is the fact that many teachers in South African schools are underqualified. In 2012, only 81 % of all practicing teachers were qualified, while 10 % were completely underqualified (CDE, 2015). The situation is even worse in physical sciences. The CDE (2011) reported that there was a shortage of 4904 physical sciences teachers in 2010 and estimated a shortage of 5135 and 5495 of such teachers in 2015 and 2025 respectively.

The landscape of science teaching in South Africa has been reported in several research studies. Some of the studies gathered physical evidence that revealed teachers' competence about teaching physical sciences using interviews and questionnaires (Basson & Kriek, 2012; Selvaratnam, 2011). Others explored teachers' views about factors that contribute to poor performance in physical sciences using interviews (Mji & Makgato, 2006). With regards to competence, it has been reported that the majority of the teachers who participated in the respective studies lacked content knowledge and problem solving strategies (Basson & Kriek, 2012; Selvaratnam, 2011). The lack of content knowledge was also pronounced by some of the teachers themselves when they outlined factors that contribute to poor performance in physical science (Mji & Makgato, 2006).

Research has also been conducted with regards to the impact of a lack of content knowledge on teachers' PCK focusing on specific topics, for example, the amount of substance and chemical equilibrium (Rollnick et al., 2008). The findings of this and other similar international studies will be described in detail in the next chapter. However, it is worth mentioning that Rollnick et al. (2008) reported that the underqualified teachers that participated in their study were ineffective in their teaching, resorting to transmission rather than the transformation of content. The studies described in this paragraph were predominantly qualitative; as such, their findings cannot be generalised to the entire country. However, they do provide evidence that some, if not many, South African learners are taught by physical sciences teachers that are ineffective.

## 1.4 ELECTROSTATICS AS A CURRICULUM TOPIC

Electrostatics is regarded as one of the important topics in introductory physics because it serves as a foundation for other topics such as electric circuits and electromagnetism (Li & Singh, 2017). In South Africa, the topic of electrostatics is taught extensively at Grade 10 and 11 according to the Curriculum, Assessment and Policy Statement (CAPS) of the DoBE (2011). Several reports in the literature have indicated that the topic of electrostatics consists of concepts that are challenging for learners both locally and internationally (Dega, Kriek, & Moghese, 2013). In South Africa, the most problematic concepts of electrostatics are taught at Grade 11. The concepts include qualitative as well as quantitative aspects of electrostatic forces and electric fields. The Grade 10 concepts of electrostatics are at an introductory level focusing on the two kinds of charges and their associated subatomic particles, charge conservation, charge quantisation and charge interactions including polarisation. As a result, the topic of electrostatics in Grade 11 was suitable for this study.

*Table 1.3: An extract of the curriculum showing the concepts and sub-concepts of electrostatics taught in Grade 11.*

| | Description | Guidelines for teachers |
|---|---|---|
| Coulomb's law | • State the law and represent it mathematically as $F = k\frac{Q_1Q_2}{r^2}$<br>• Solve 1D and 2D problems using this law | • Link Coulomb's law with Newton's law of universal gravitation.<br>• Represent electrostatic forces using free body diagrams and explain the application of Newton's third law.<br>• Emphasise that signs of charges must not be substituted into Coulomb's law.<br>• Discuss the application of the principle of superposition to determine the resultant force in a straight line or 2D.<br>• Restrict 2D problems to charges at right angles with the reference charge placed at the right angle. |
| Electric field | • Describe what an electric field is and indicate how its direction is determined.<br>• Represent an electric field around a charged object with a drawing. | • Relate electric fields with magnetic fields taught in Grade 10.<br>• Emphasise that electric field lines are drawn closer to each other where the field is stronger. |
| Electric field strength | • Define it as the force per unit charge, $E = \frac{F}{q}$ whereby E and F are vectors.<br>• Deduce $E = k\frac{Q}{r^2}$ using Coulomb's law and the definition of electric field strength.<br>• Solve problems involving the electric field strength. | • Solve problems limited to a single dimension.<br>• Emphasise that the signs of charges need not be included when calculating the electric field. |

The three fundamental concepts outlined in Table 1.3; electrostatic force, electric field and electric field strength, reveal different learners' alternative conceptions both locally and internationally. The challenges faced by learners in these concepts are discussed in the next two sections starting with an international overview before looking at the difficulties faced by South African learners.

### 1.4.1 Learners' difficulties in understanding electrostatics

Several challenges that are associated with the three fundamental concepts of electrostatics are documented in the literature. In terms of the electrostatic force, it has been reported that some learners find it difficult to understand the inverse square relationship between force and distance (Ajredini, Izairi, & Zajkov, 2013; Maloney, O'Kuma, Hieggelke, & Heuvelen, 2001). In particular, the learners believe that halving the distance between charges strengthens their force of interaction by a factor of two. Furthermore, it has been reported that some learners tend to substitute signs of charges into Coulomb's law and as such, they regard the sign of the final answer as an indication of direction (Huynh & Sayre, 2018). Difficulties have also been reported with regards the application of Newton's third law whereby learners think that bigger charges exert stronger forces on smaller ones (Ajredini et al., 2013; Bohigas & Periago, 2010; Maloney et al., 2001).

In terms of the electric field, it has been reported that learners tend to associate the electric field at a point with the test charge placed at that point (Li & Singh, 2017). As such, they believe that when the test charge is removed, then the electric field ceases to exist at that point (Bohigas & Periago, 2010). It is also documented in the literature that some learners struggle with drawing and/or interpreting electric field lines. When asked to draw electric field patterns, some learners draw field lines that touch or cross (Taskin & Yavas, 2019). In terms of the interpretation of field lines, it has been reported that some learners regard electric field lines as being real and as a medium through which electrostatic forces are transmitted between charges (Pocovi & Finley, 2002). Furthermore, some learners do not infer the electric field strength from the density of electric field lines (Torkvist, Pettersson, & Transtromer, 1993). Instead, they believe that the electric field strength remains the same along an electric field line (Saarelainen, 2007).

In terms of the electric field strength, a concept that is associated with calculations of the strengths of electric fields, the following challenges are documented in the literature. It has been reported that learners find it difficult to distinguish between the charge (Q) that creates an electric field and the charge (+q) that tests the field (Bohigas & Periago, 2010). Similar to the calculation of electrostatic forces, some learners substitute signs of charges when determining the electric field. As such, they regard the sign of the final answer as an indication of the direction of the electric field (Huynh & Sayre, 2018). It has also been reported that some learners find it difficult to determine the resultant electric field at a point due to multiple charges (Li & Singh, 2017). In particular, they believe that the electric fields of like charges always add up at any point while those of unlike charges always cancel each other out (Li & Singh, 2017).

### 1.4.2 South Africa's learners' difficulties in understanding electrostatics

Learners in South Africa are no exception to the global problem associated with difficulties in understanding electrostatics. At the end of each academic year, the DoBE releases diagnostic reports on the performance of learners in the Grade 12 national examinations. The reports have consistently shown that electrostatics forms part of the topics in which learners perform poorly, with the average performance in electrostatics ranging between 18% and 54% from 2011 to 2018.

The diagnostic reports also specify the challenges identified in learners' responses to the test items used in the examinations. Furthermore, the reports also provide recommendations for teachers to improve the performance of their learners. The difficulties reported in the diagnostic reports are similar to those that are documented in the literature. For example, it has consistently been reported that some learners do not understand the difference between an electrostatic force and an electric field (DoBE, 2015; 2017; 2018). Careful analysis of the reports has revealed that when the concept of an electrostatic force and that of the electric field were documented separately, learners tended to perform slightly better in electrostatic forces (DoBE, 2015; 2017). This finding has also been reported by Garza and Zavala (2013), whereby their participating learners performed better in electrostatic forces than they did in electric fields.

## 1.5 PROBLEM STATEMENT

It has been well argued that PCK is a teacher professional knowledge base that serves as the cornerstone of teacher effectiveness (Cochran et al., 1991; Eames, Williams, Hume & Lockley, 2011). However, it took a while before researchers started to explore the effectiveness of teachers' PCK against the evidence of learning from the learners that they taught. Other scholars have echoed the same sentiment that learning outcomes serve as evidence of teacher effectiveness (Carlson & Daehler, 2019). At the time of the PCK research literature by Abell (2008), she noticed that there was a paucity of information about the relationship between teachers' PCK and evidence of learning. The element of learners' outcomes has actually been side-lined from the original conception of PCK by Shulman (1986, 1987).

Many years later at the first PCK summit, Shulman (2015, p. 10) admitted that his original conception of PCK did not pay attention to the "relationship between teaching and the evidence of learning". In recent times, however, there have been a few studies that investigated the relationship between teachers' PCK and learners' outcomes (e.g. Alonzo, Kobarg, & Seidel., 2012; Gess-Newsome, Taylor, Carlson, Gardner, Wilson, & Stuhlsatz, 2017). The findings reported in the respective studies were in conflict, which Chan and Hume (2019) attributed to the different methodologies adopted. Some of the studies inferred teachers' PCK from sources that are distant from actual classroom teaching, for example, teachers' descriptions of their own teaching (Hill, Rowan & Ball, 2005; Kanter & Konstantopoulos, 2010). Others inferred PCK and learners' outcomes from secondary data that contained video-recorded lessons of teachers as well as the pre and the post-test results of the learners (Alonzo et al., 2012). Although this line of research is steadily growing, the relationship between teachers' PCK and learners' outcomes is still very hazy.

## 1.6 RATIONALE

As indicated earlier, the quality of science teaching and learning in South Africa is predominantly poor. The poor performance of South African learners has been attributed to a variety of factors, including the quality of teaching that they receive (Howie & Plomp, 2006; Reddy, 2006). However, studies that explore the relationship between the quality of teaching through the lens of PCK and learners' outcomes in South Africa are yet to be conducted to investigate these attributions. As indicated earlier, this growing line of research has revealed contrasting results. Furthermore, most of the studies inferred teachers' PCK from data sources that are divorced from classroom teaching, conforming to the original conception of PCK that focused on the pedagogical mind rather than action (Shulman, 2015). This conception of PCK has been criticised for obscuring other crucial aspects of teachers' knowledge for teaching, especially the skill needed to carry out classroom instruction (Grossman et al., 2009). Recently, many scholars have advocated the importance of making practice the centre of teacher education (Grossman, Hammerness, & McDonaldo, 2009; Lowenberg-Ball & Forzani, 2009), thus highlighting the need for exploring and developing practice-based aspects of PCK in real classroom settings (Alonzo & Kim, 2016). This is particularly important following my earlier research finding that the knowledge that teachers demonstrate in writing is not necessarily a true reflection of their actual teaching (Mazibe, Coetzee, & Gaigher, 2020).

This study builds on the taxonomy of PCK developed by Veal and MaKinster (1999). Their taxonomy paved the way for the development of a model that describes teachers' knowledge at topic-specific level by Mavhunga and Rollnick (2013). While using this model to explore teachers' PCK about graphs of motion (Mazibe et al., 2020), I came to realise that it is difficult to collectively describe an individual teacher's PCK about a specific topic because their competence seemed to vary across concepts. I have also observed that learners' outcomes also tend to vary across concepts within a topic. The need for exploring teachers' PCK and learners' outcomes by focusing on specific concepts is thus evident. This way, the PCK of the teachers and the outcomes of their learners can be attributed to specific concepts rather than the entire topic. In terms of PCK, such an investigation will provide empirical evidence that supports or refutes the notion that PCK has a concept specific nature (Carlson & Daehler, 2019; Smith & Banilower, 2015).

Apart from being challenging for learners, the topic of electrostatics was also chosen for this study because it had seldom been investigated in terms of PCK (Melo, Canada & Mellado, 2017; Melo-Nino, & Mellado, 2017), particularly at the concept level. The researchers investigated (i) the initial characterisation of in-service teachers PCK and (ii) the teachers' emotions in relation to their PCK at topic level. In the first study, they formulated concepts in which they compared the quality of their participating teachers' PCK. They found that there were similarities in terms of teaching strategies and content evaluation, whereas differences emerged in the teachers' understanding of the importance and the sequence in which the concepts must be taught (Melo-Nino et al., 2017). In the second study, they reported that the positive and negative emotions of the teachers varied across concepts of electrostatics (Melo-Nino et al., 2017). The present study aims to extend the existing body of knowledge about PCK in electrostatics by exploring it at the concept level and relating it to learners' outcomes.

## 1.7 PURPOSE OF THE STUDY

The purpose of this study is to investigate the relationship between teachers' PCK and learners' outcomes at the concept-specific level. As indicated earlier, the topic of electrostatics includes three concepts that reveal different learner alternative conceptions. The concepts are as follows; electrostatic force, electric field and electric field strength. The PCK of the teachers and the outcomes of the learners will be explored within these three concepts before they are related. I believe the results of study will extend the body of knowledge in two ways. Firstly, because the acknowledgement of the concept-specific grain size of PCK is fairly recent, empirical evidence of PCK in this grain size is still missing (Mazibe, Gaigher, & Coetzee, 2020). As such, the results may indicate whether it is appropriate to consider PCK at concept level. Secondly, the relationship will be investigated at the concept specific grain size by relating the quality of teachers' PCK about the concepts of electrostatics and learners' outcomes in those concepts. In this study, the static knowledge of teachers, termed "personal PCK" and their dynamic knowledge, termed "enacted PCK" will be explored and related to the outcomes of the learners. The research questions that guided this study are presented in the next section.

## 1.8 RESEARCH QUESTIONS

### 1.8.1 Primary question

- What is the relationship between teachers' PCK and learners' outcomes in specific concepts of electrostatics?

### 1.8.2 Secondary questions

The primary research question was deconstructed to formulate the following secondary research questions:

- How does personal PCK compare across specific concepts of electrostatics for selected teachers?
- How does enacted PCK compare across specific concepts of electrostatics for the selected teachers?
- How does the achievement of learning outcomes compare across specific concepts of electrostatics for participating learners?

## 1.9 RESEARCH ASSUMPTIONS

This study was designed and conducted under certain assumptions about the intended data that would be collected from the participants. Although it is well documented that PCK is tacit and therefore difficult to explore, I am assuming that PCK can be portrayed by teachers in their written accounts about their teaching, their lesson presentations and their responses to interview questions. Furthermore, I am assuming that learners' responses to the test items indicate their level of performance. Based on these assumptions, it is thus claimed that the data that will be collected for this study will reflect the PCK of the teachers and the performance of their learners.

### 1.10 CHAPTER SUMMARY

In this chapter, I have provided an overview of a study that was aimed at investigating the relationship between teachers' PCK about electrostatics and learners' performance at the concept level. I started by describing PCK briefly as well as the South African schooling context in which the present study will be conducted. I have also unpacked the topic of electrostatics by describing its fundamental concepts that are chosen for this study as well as learners' difficulties in the concepts both locally and internationally. Furthermore, I described the research problem, the rationale for conducting this study, the research questions, as well as the assumptions on which the study was based. In the next paragraph I will describe the upcoming chapters in this thesis.

In chapter two I will describe the literature that has been consulted in terms of the PCK construct as well as the topic of electrostatics in greater detail. In particular, I will focus on the models and components of PCK. In chapter three I will outline the research methodology, in particular, the strategies that I have used to collect and analyse data to answer the formulated research question and address the research problem. In chapter four and five, I will describe the personal and the enacted PCK of the participating teachers across the fundamental concepts of electrostatics, respectively. In chapter six, I will present and describe the performance of the participating learners across the fundamental concepts of electrostatics. Chapter seven will describe how the outcomes of the learners relate to teachers' personal and enacted PCK respectively. Finally, chapter eight will describe the conclusion drawn from the study as well as the limitations and the recommendations for future research and practice.

## 2. CHAPTER TWO: LITERATURE REVIEW

### 2.1 INTRODUCTION

This chapter presents a review of the literature that is relevant and applicable to this study in detail. In particular, I will discuss the literature that I have reviewed with regard to the PCK construct and the topic of electrostatics. In terms of PCK, the discussion will include different scholars' conceptualisations of the construct, particularly its components and how the components were fitted together in different models that describe teacher knowledge. Furthermore, I will discuss the models of teacher knowledge that I have chosen as the conceptual frameworks for this study. The review also includes a discussion of the quality of experienced and novice teachers, which is related to the sampling of participants as discussed in the next chapter. Moreover, I will discuss the strategies and techniques that have been used to capture and assess PCK as well as how they related learners' outcomes to teachers' PCK. In terms of electrostatics, I will describe learners' challenges in the topic both locally and internationally, as well as the recommended strategies for teaching the topic.

### 2.2 THE PLACE OF PCK IN TEACHING AND RESEARCH

After Shulman proposed the concept of PCK, several scholars adopted and adapted his ideas to suit their research. He originally described it as "subject matter knowledge for teaching", indicating that it goes beyond teachers' content knowledge entailing how the content is transformed into teachable units (Shulman, 1986, p. 9).

#### 2.2.1 Components of PCK

Perhaps the way PCK was described by Shulman (1986, 1987) revealed the complexity of the construct (Baxter & Lederman, 1999; Kagan, 1990). In the 1986 paper, Shulman regarded PCK as a sub-category of content knowledge, whereas in the 1987 paper, he regarded it as a category alongside six other teacher knowledge bases including content and pedagogical knowledge (Hashweh, 2005). The other four knowledge bases were; curriculum knowledge, knowledge of learners and their characteristics, knowledge of educational contexts, and the knowledge of educational ends, purposes and values, and their philosophical and historical backgrounds. Furthermore, the knowledge of learners and of instructional strategies was regarded as the foundation of PCK by Shulman (1987). Although scholars'

*Table 2.1: Components of PCK derived from different studies.*

| **Study** | **Content** | **Pedagogy** | **Context** | **Learners' understanding** | **Instructional strategies and representations** | **Curriculum** | **Purposes for teaching a subject** | **Assessment** |
|---|---|---|---|---|---|---|---|---|
| Alonzo and Kim (2016) | X | Y | Y | PCK | PCK | X | Y | X |
| Cochran, DeRuiter, and King (1991) | PCK | PCK | PCK | PCK | Y | Y | Y | Y |
| Geddis (1993) | Y | Y | Y | PCK | PCK | PCK | Y | Y |
| Grossman (1990) | X | X | X | PCK | PCK | PCK | PCK | Y |
| Hashweh (2005) | PCK | PCK | PCK | PCK | PCK | PCK | PCK | PCK |
| Loughran, Berry, and Mulhall, (2006) | PCK | PCK | PCK | PCK | PCK | Y | PCK | Y |
| Magnusson et al. (1999) | X | X | X | PCK | PCK | PCK | PCK | PCK |
| Park and Chen (2012) | X | X | Y | PCK | PCK | PCK | Y | PCK |
| Rollnick et al. (2008) | PCK | PCK | PCK | PCK | PCK | PCK | X | PCK |
| Shulman (1987) | X | X | X | PCK | PCK | X | X | Y |
| Van Driel, Verloop, and de Vos (1998) | X | Y | Y | PCK | PCK | Y | Y | Y |

Adapted from Kirschner, Borowski, Fischer, Gess-Newsome, and von Aufscnaiter (2016)

Key: X – Explicitly excluded from PCK, PCK – Explicitly included in PCK, Y – Not discussed thoroughly.

conceptualisations of the makeup of PCK is predominantly different among themselves, they agree with Shulman's two components of PCK (see Table 2.1). The scholars have also added other aspects of teachers' knowledge that are part of PCK following that Shulman regarded them as being distinct from PCK. Magnusson's et al. (1999, p.15) argument in this regard was that PCK refers to "the transformation of several types of knowledge for teaching" including the knowledge bases that Shulman (1987) had regarded as being distinct from PCK. Table 2.1 summarises PCK components proposed by other researchers. The distinctive features of each of these PCK components are discussed below.

***Content knowledge***

Content knowledge (CK) refers to the understanding of major facts, concepts and principles within a field, comprising of substantive and syntactic structures of knowledge (Grossman, 1990). Substantive structures refer to the organisation of a discipline; indicating how facts and concepts within the discipline are related (Schwab, 1962). Syntactic structures refer to the understanding of processes of knowledge construction; methods of inquiry, evidence that supports facts as well as the evaluation of the knowledge by experts (Schwab, 1962). Different terminologies are used in literature to describe content knowledge including subject matter knowledge (SMK), conceptual knowledge (Gess-Newsome, 1999), and academic content knowledge (ACK) (Gess-Newsome et al., 2017). When content knowledge is transformed for instruction, it becomes what Gess-Newsome et al. (2017) termed "PCK-CK", which refers to the correctness of concepts, links between concepts within and across topics and the nature of science, as well as the use of multiple representations and examples in a topic. According to Smith and Banilower (2015), PCK is inextricably tied to CK because it refers to its transformation. As such, without CK, there can never be PCK. Their argument was as follows:

> *"PCK can also be judged against the components of PCK. For example, if a teacher's PCK incorporates incorrect science content knowledge, then the resulting PCK would, by definition, be incorrect"* (Smith & Banilower, 2015, p. 92).

Several PCK studies have shown that CK is necessary, yet it is insufficient on its own to produce effective classroom instructions (Cochran et al., 1991; Gess-Newsome, 1999; Rollnick et al., 2008). In the literature, studies that investigated the relationship between content knowledge and PCK have reported inconsistent results (Jüttner, Boone, Park, & Neuhaus, 2013). It is naïve to assume that a developed content knowledge, or a lack thereof, will necessarily be translated to the same level in terms of PCK (Bukova-Guzel, Kula, Ugurel & Ozgur, 2010; Buschang, Chung, Delacruz & Baker, 2012). Some researchers have reported cases where teachers that possessed rich knowledge of the content failed to transform it well for instruction (Rollnick & Mavhunga, 2014; van Driel et al., 1998) while in other studies the results were opposite (Davidowitz & Vokwana, 2014; Kind, 2009b). While the results of the former studies are common, particularly in the cases of pre-service teachers because of a lack of teaching experience which is one of the sources of PCK development (Kind, 2009a), those of the latter studies are unexpected. For example, in the study by Davidowitz and Vokwana (2014), it was reported that two of the participating teachers performed better in the PCK questionnaires while they performed poorly in the CK test. The scholars also reported that they interviewed one of the teachers to investigate the cause of the mismatch between their CK and PCK. It was found that the participant ran workshops for in-service teachers focusing specifically on pedagogy only. Similar results were reported by Kind (2009b) where the participating pre-service teachers enrolled for a postgraduate certificate in education (PGCE) were required to teach inside and outside of their topic specialisations. It was reported that the participants were successful when they taught outside of their specialisations, particularly at the beginning of their PGCE course. According to Kind (2009b), this outcome was caused by the fact that the pre-service teachers requested help from experts when they were planning to teach unfamiliar topics. With regards to familiar topics, they were reluctant to request expert assistance because it would signal weakness in their knowledge.

It is evident in the literature that content knowledge shapes teachers' PCK through other components. For example, the knowledge of learners' understanding (Childs & McNicholl, 2007), conceptual teaching strategies (Halim & Meerah, 2002) and assessment relies on a solid understanding of the content.

### *Pedagogical knowledge*

Many scholars' descriptions of pedagogical knowledge (PK) have revealed variations. Nevertheless, there is consensus that classroom management is a key component of PK (Kind & Chan, 2019; Shulman, 1986). According to Kind and Chan (2019), content knowledge has little impact on learning if it is delivered in environments that are not conducive to learning. As such, it is important to manage a class in a way that creates a positive and constructive learning environment (Kind & Chan, 2019). Other aspects of PK that are reported in the literature include teaching strategies, the organisation of resources and materials (Kind & Chan, 2019) and the assessment of learners' performance (Liepertz & Borowski, 2019). According to Kind and Chan (2019), teachers need to develop teaching strategies that capture learners' attention and those that lead to learning. Gess-Newsome et al. (2017) on the other hand distinguished two forms of pedagogical knowledge – general pedagogical knowledge (GenPK) and PCK-pedagogical knowledge (PCK-PK). GenPK, described as the ability to implement general teaching skills (Gess-Newsome et al., 2017), was identified as a component of teachers' professional knowledge similar to PCK, whereas PCK-PK was regarded as an internal construct of PCK. They described PCK-PK as a rationale that links pedagogical reasons with learners' thinking, which enables teachers to elicit learners' prior knowledge and promote conceptual understanding. Based on these descriptions of PK in the literature, it is evident that teaching experience is a major source of teachers' PK because of the teaching skills that need to be developed through actual teaching (Nilsson, 2008).

***Contextual knowledge***

According to the information summarised in Table 2.1, a few scholars regarded contextual knowledge as a component of PCK. In his reflection about the PCK construct, Shulman (2015) indicated that his theorisation of PCK did not pay attention to social and cultural contexts. He regarded these contexts as envelopes in which aspects of teaching and learning are located. Many researchers agree with this notion, including Gess-Newsome (2015, p. 37) who indicated that "beyond what teachers know and believe, instruction is shaped by a specific classroom context". It is thus very important for teachers to have a deep understanding of the learning context including contextual factors ranging from those that are far removed to those that are closer to their learners (Carlson & Daehler, 2019). This is how Loughran et al. (2006, p. 2) described the importance of contextual knowledge into teachers' PCK:

> *It [pedagogical reasoning] is a window into the thoughtful and skilful act of practice that is responsive to the given context, i.e. there is not the assumption that the same thing works the same way all of the time. The ability to adapt, adjust and make appropriate professional judgments, then, is crucial to shaping the manner in which teachers teach and respond to their students' learning.* (Loughran et al., 2006, p. 2)

Several contextual factors have been reported in PCK literature including districts, school settings, resources, class size, learners' socio-economic status, curriculum materials, teachers' workloads and learners' attributes (Gess-Newsome, 2015; Rollnick et al., 2008). It is through these contextual factors that the knowledge that is shared by a community of teachers becomes personalised into unique PCK that is held by individual teachers (Carlson & Daehler, 2019).

***Knowledge of learners' understanding***

As shown in Table 2.1, the knowledge of learners' understanding is mostly included as a component of PCK. Teachers need to be aware of learners' typical misconceptions and difficulties, and to use this awareness to shape their practice (Loughran, Mulhall, & Berry, 2004). When teachers acquaint themselves with the knowledge of areas of learners' difficulties and misconceptions, they formulate effective strategies to uncover their learners' understanding or a lack thereof (Magnusson et al., 1999). Furthermore, they use this knowledge to address unanticipated misconceptions that may show during teaching (Alonzo & Kim, 2016). According to Park and Oliver (2008a), addressing unanticipated difficulties develops teachers' PCK even further. Literature shows that content knowledge plays a major role in this PCK component and that a lack of content knowledge limits teachers' awareness of learners' understanding of concepts (Halim & Meerah, 2002; van Driel et al., 1998). In some instances, it is the teachers themselves that hold some of the misconceptions (Hashweh, 1987) which they inevitably transfer to their learners during teaching (Mazibe et al., 2020; Mdolo & Mundalamo, 2015). Sometimes they may regard correct concepts as typical misconceptions revealed by learners (Halim & Meerah, 2002; Mazibe et al., 2020). Furthermore, a lack of content knowledge also makes it difficult to elicit misconceptions because teachers seldom ask conceptual questions, as they would not have the answers to those questions themselves (Childs & McNicholl, 2007). It is, therefore, clear that content knowledge influences teachers' awareness of learners' misconceptions and ultimately affects their instructional strategies.

***Instructional; strategies and representations***

As indicated earlier, many PCK researchers believe that teachers' knowledge of this component is shaped by their awareness of learners' thinking and understanding

(Park, Suh & Seo, 2018; van Driel, De Jong, & Verloop, 2002;). Grossman (1990, p. 9) mentioned that "to generate appropriate explanations and representations, teachers must have some knowledge about what students already know about a topic and what they are likely to find puzzling" (Grossman, 1990, p. 9). In science education literature, several instructional strategies have been designed based on teachers' awareness of learners' typical misconceptions, for example, cognitive accommodation (Nussbaum & Novick, 1982) and conceptual change text (Ersoy & Dilber, 2014). When using these strategies, teachers must design an exposing event, which could be questions or a practical activity that requires learners to apply knowledge and consequently reveal their misconceptions (Nussbaum & Novick, 1982). Teachers must then create a discrepant event which induces cognitive conflict between learners' misconceptions following the realisation that their ideas cannot explain the observed phenomenon (Nussbaum & Novick, 1982). Finally, teachers can guide learners in their search for solutions and subsequently build new knowledge by providing correct explanations (Ersoy & Dilber, 2014).

Knowledge of a variety of teaching strategies is an important aspect of PCK (Loughran, et al., 2006). The knowledge of strategies enhances teachers' PCK when it is combined with the knowledge of learners' understanding (van Driel et al., 1998). Teachers' ability to select and effectively utilise teaching strategies during teaching is influenced by their knowledge of the content. Teachers who lack content knowledge predominantly use direct instruction (Halim & Meerah, 2002) by presenting facts as they are in their teaching materials (Childs & McNicholl, 2007) as well as by using procedural teaching and algorithms (Rollnick et al., 2008). Furthermore, some of the representations and analogies used by teachers that lack sufficient content knowledge have the potential to induce misconceptions (Halim & Meerah, 2002).

***Knowledge of the curriculum***

This component refers to teachers' knowledge of curricular materials available for teaching a topic comprising of vertical and horizontal curricular knowledge (Grossman, 1990). The vertical knowledge refers to the knowledge of what learners have learnt in previous grades and what they will learn in the next grade levels (Grossman, 1990; Hashweh, 2005). The horizontal knowledge refers to teachers' understanding of the curriculum in the same grade (Hashweh, 2005). In a review study by Davis, Janssen and van Driel (2016), it has been reported that PCK and curriculum knowledge influence each other. PCK helps teachers make decisions that are related to the curriculum, for example eliminating challenging concepts or including mandatory prerequisite ideas (Lee, Brown, Luft & Roehrig, 2007; Rollnick et al., 2008). An example of the impact of curriculum knowledge on teachers' practice was reported in the study by Rollnick et al. (2008). The study aimed to explore the place of content knowledge on teachers' practice in the case of underqualified teachers. It was reported that the participating teachers deviated from the prescription of the curriculum and predominantly focused on algorithms. According to the researchers, this outcome was caused by the teachers' lack of content knowledge and the fact that the teachers were preparing learners to pass examinations at the expense of understanding the concepts.

***Purposes for teaching a subject***

This component, described as "orientations towards teaching science" by Magnusson et al. (1999), refers to teachers' beliefs and goals about the purpose of teaching a subject (Grossman, 1990). Magnusson et al. (1999) regarded this knowledge base as a central component in PCK because it shapes other knowledge bases. For example, teachers' beliefs guide their selection of teaching strategies. Those who believe in discovery, inquiry or activity driven approaches (more orientations listed in the article) might select practical investigations as a teaching strategy (Magnusson et al., 1999). Thus a single strategy can be characteristic of a variety of beliefs, which suggests that teachers' PCK is not indicated by the strategies employed, but rather by the *purpose(s)* of employing those strategies (Magnusson et al., 1999).

***Assessment***

How does one know that teaching and learning is/has taken place effectively? This component answers this question. It refers to teachers' knowledge of the concepts that are important for assessment, as well as the methods, activities, instruments and approaches of assessment (Park & Oliver, 2008a). Content knowledge plays an important role in this component, as indicated earlier. A lack of content knowledge makes it difficult for teachers to engage in assessment because they ask lower-order questions that they can easily answer (Mizzi, 2013). When teachers lack the knowledge of the concepts that they are teaching, it becomes difficult for them to ascertain if learning is taking place or not.

### 2.2.2 Realms of PCK

In this section of the review, I will discuss scholars' perceptions of PCK pertaining to its generalisation. Ever since Shulman (1986) introduced PCK, some scholars have always conceptualised it as being personal, private (Hashweh, 2005) and unique to individual teachers (Cochran et al., 1991). Such personal PCK develops through personal experience informed by contextual factors, lesson preparation, lesson presentation and reflection (Loughran et al., 2004). Smith and Banilower (2015) argued that while PCK can be personal and as such different from one individual to another, there must be a collective form of PCK that is ideally shared by experts. This collective knowledge was termed canonical PCK. They described canonical PCK as the knowledge that belongs to the teaching profession, as opposed to being personal and private to individuals. They also added that this knowledge is generated through research and is agreed upon by collective insights of experts (Hashweh, 2005; Loughran et al., 2004; Rollnick et al., 2008). Personal and canonical PCK shape each other. Canonical PCK becomes personal when teachers put it into practice, while personal PCK becomes canonical when it is shared by many expert individuals (Smith & Banilower, 2015). Similarly, Park and Suh (2015) identified two aspects of PCK, which they named indispensable and idiosyncratic PCK. Indispensable PCK refers to the forms of PCK that are universal, that is, they can be applied to any context by any teacher to teach any topic, while idiosyncratic PCK refers to forms that are unique to individual teachers and contexts. These scholars shared a similar conception of the PCK construct, arguing that just as content knowledge is universal regardless of educational settings and contexts, there should be aspects of PCK that are universally accepted. Hence Park and Suh (2015) regarded canonical science as well as learning theories as the constituents of indispensable PCK, whereby a teacher transform his/her canonical content knowledge into a teachable form through aligning it with learning theories. These aspects of PCK are important in the sense that they support the standardisation of PCK that can be used to measure the personal PCK of individuals.

## 2.3 MODELS OF PCK

In this section of the review, I will be discussing scholars' PCK models based on the consolidations of the components summarised in Table 2.1. I will focus on the commonly cited models in PCK studies at the time of the present study and also the models that I have chosen to guide this study.

### 2.3.1 Early PCK models

The most cited PCK models in literature at the time of the present study were developed by Grossman (1990) and Magnusson et al. (1999). In Grossman's (1990) model, PCK is shaped by teachers' knowledge of learners' understanding, knowledge of the curriculum, knowledge of instructional strategy and an overarching component–teachers' conceptions of purposes for teaching content. This overarching component refers to teachers' beliefs, purposes and goals for teaching a topic at a certain grade (Grossman, 1990). Magnusson et al. (1999) drew from Grossman's model and added knowledge of assessment (of scientific literacy) as the fifth component of PCK. They also changed Grossman's overarching PCK component into "orientations to teaching science". Similar to Grossman (1990), Magnusson et al. (1999) conceptualised orientations as the knowledge of the goals and purposes for teaching a topic, and regarded it as the central component of PCK which shapes (while it is also shaped by) the other components. In addition, Magnusson et al. (1999) preferred the term "orientations", which was originally used by Anderson and Smith (1987), claiming that it also "represents a general way of viewing or conceptualising science teaching" (p. 97).

Although Magnusson et al.'s (1999) model has been used in science education studies since its development, scholars have recently criticised it. Nezvalova (2011) mentioned that orientations are generalised conceptions about teaching science as opposed to being specific to a science topic, and as such, they are not strictly regarded as knowledge structures. Another challenge is the fact that there are different, and thus inconsistent, definitions and interpretations of orientations in the original development of the model (Friedrichsen, van Driel & Abell, 2011) and its deployment by other scholars in their studies (Nezvalova, 2011). On the one hand, orientations refer to purposes and goals for teaching, as in the case of Grossman (1990) while on the other hand they refer to teachers' general ways of viewing teaching, connected with teachers' actions (Anderson & Smith, 1987). Furthermore, the scholars did not explicitly explain or demonstrate how the "central" PCK component, "orientations to teaching science", shapes and is shaped by the other components (Kind & Chan, 2019).

The models by Grossman (1990) and Magnusson et al. (1999) also guided the development of other PCK models, for example the hexagon (Park & Oliver, 2008a) and the pentagon model of PCK (Park & Chen, 2012; Park & Oliver, 2008b; Park et al., 2018). These models of PCK reflected the integrative model of teachers' professional knowledge bases introduced by Gess-Newsome (1999), whereby PCK was regarded as the intersection of various teacher knowledge bases. Gess-Newsome (1999) used mixtures as an analogy to explain the integrative model stating that the knowledge of content, context and pedagogy are developed separately and integrated during teaching while retaining their distinctive features. The limitation of this model is that it relies on the coherent integration of the knowledge bases (Park & Oliver, 2008a). For example, emphasising content over pedagogy might lead to a teaching strategy that promotes the transmission of raw, untransformed content to learners (Gess-Newsome, 1999). Furthermore, an improvement in one of the components is insufficient for effective teaching although it may encourage the development of other components and ultimately PCK (Park & Oliver, 2008a). The models also conformed to the transformative model whereby PCK was regarded as a separate, but not as a free-standing type of knowledge (Abell, 2008; Kind, 2009a), while the other knowledge bases served as latent resources synthesised into PCK (Gess-Newsome, 1999). While Magnusson et al.'s (1999) model only described the interaction between 'orientations to science teaching' and the other components (Friedrichsen et al., 2011), the models by Park and colleagues describe the interactions among all the components. Furthermore, the models placed PCK in practice by describing the reflections of teachers in and on practice while they are integrating the five components of PCK. The first model was termed 'the hexagon model' because it consisted of a sixth component of PCK which was termed "teacher efficacy" (Park & Oliver, 2008a). Teacher efficacy describes teachers' confidence in their abilities to teach effectively and thus acts as a conduit between their personal and enacted knowledge (Park & Oliver, 2008a). This component was no longer included in the subsequent pentagon model and the reason behind this decision is not clear (Park & Oliver, 2008b; Park & Chen, 2012; Park et al., 2018).

### 2.3.2 Topic Specific PCK models

Veal and MaKinster (1999) introduced a taxonomy that classifies PCK into three levels of generalisation, namely: general PCK, domain-specific PCK and topic-specific PCK. General PCK, which Magnusson et al. (1999) termed subject-specific PCK, refers to teachers' knowledge of teaching subjects, for example, science, English, arts, history and mathematics. The models by Grossman (1990) and Magnusson et al. (1999) describe knowledge for teaching subjects, for example science. Although the orientations of general PCK can be applied in different subjects, the approaches, strategies, content and purposes will differ and be specifically inclined to the subject taught (Nezvalovà, 2011). For example, a history teacher might represent a timeline of historical events using drawings, similar to a science teacher using drawings to explain phase changes from solid to gas or vice versa. The second level of PCK, domain-specific PCK, refers to an area of discipline within a subject, "the content area of science" (Nezvalovà, 2011, p. 107), for example physics, chemistry or biology. The third level of generalisation, topic-specific PCK is regarded as the most specific and novel level of teacher knowledge (Veal & MaKinster, 1999). Furthermore, teachers that are knowledgeable at the topic-specific PCK level are expected to have a solid repertoire of skills and abilities in the previous levels (Veal & MaKinster, 1999).

Many of the models that describe PCK focused on identifying components of PCK (Cochran et al., 1991) and outlining the interactions between the components (Park & Oliver, 2008a). Rollnick et al. (2008) developed a model that did not only describe the amalgam of knowledge bases that shape PCK, but also outlined the products of PCK that are visible in practice, which they termed "manifestations". The manifestations were, but not limited to, curricular saliency, representations, topic-specific instructional strategies and assessment. The model was later modified by Davidowitz and Rollnick (2011) whereby they added "beliefs", as a factor that influences, and is equally influenced, by teachers' knowledge bases. They also added "explanations" and "interactions with students" as products of PCK while "assessment" was excluded in the model following a lack of evidence from the data that they collected. These models were developed based on specific topics; the amount of substance and chemical equilibrium (Rollnick et al., 2008) as well as organic chemistry (Davidowitz & Rollnick,

2011) respectively. These models, therefore, provided a solid foundation for the development of a single model that describes teachers' PCK about specific topics.

Although scholars have been exploring PCK within specific topics, it was Mavhunga and Rollnick (2013) who developed a model that describes the transformation of topic specific content into teachable forms. They referred to the manifestations by Rollnick et al. (2008) and a later updated version by Davidowitz and Rollnick (2011) to develop their model which they termed Topic Specific PCK (TSPCK) (Figure 2.1). In the model, the transformation of specific content emerges from five components of teacher knowledge, namely; learners' prior knowledge including misconceptions, curricular saliency, what is difficult to teach, representations including analogies, and conceptual teaching strategies. Knowledge of curricular saliency includes teachers' understanding of key concepts and their importance in the topic, the sequence in which the concepts should be taught and the ability to leave certain aspects of a topic for future lessons (Rollnick et al. 2008).

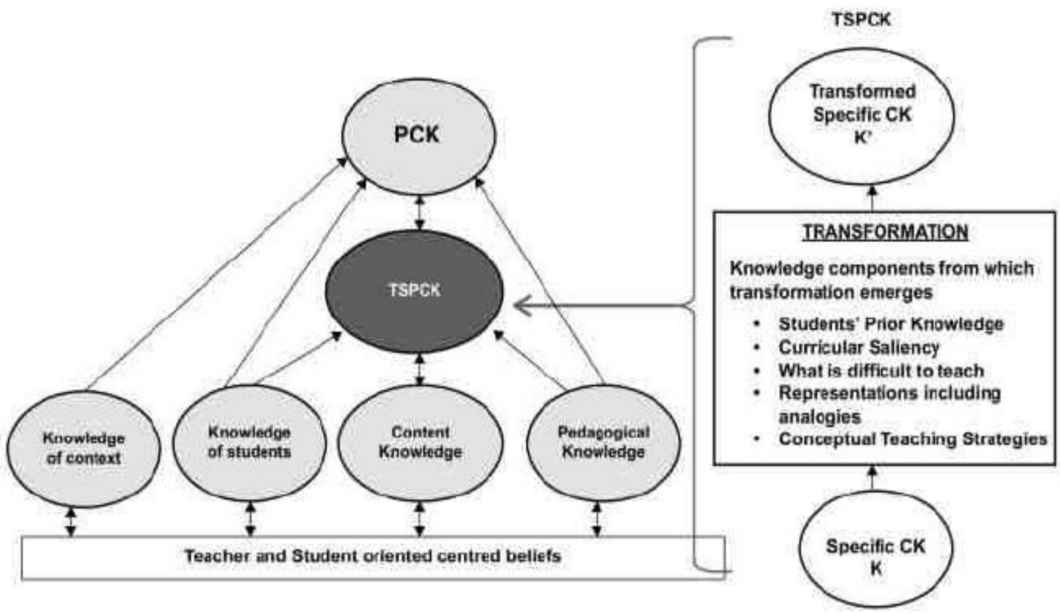



*Figure 2.1: The topic-specific PCK model (Mavhunga & Rollnick, 2013).*

Scholars have used this model to frame their studies in different topics including particulate nature of matter (Pitjeng-Mosabala & Rollnick, 2018), electrochemistry (Rollnick & Mavhunga, 2014), genetics (Mdolo & Mundalamo, 2015) and graphs of motion (Mazibe et al., 2020). Other scholars in the PCK literature used Magnusson et al.'s (1999) model to investigate teachers' PCK about specific topics, for example, photosynthesis and plant growth (Käpyla, Heikkinen, & Asunta, 2009), the solar system and the universe (Henze, van Driel, & Verloop, 2008) and ozone layer depletion (Kaya, 2009). The current study adopted Mavhunga and Rollnick's (2013) model because its precise description of teachers' PCK about specific topics is useful to frame a study focusing in detail on the teaching of the content of a specific topic, electrostatics.

### 2.3.3 The consensus model of PCK

Given the differences in the conceptualisation of PCK by many researchers, a PCK summit was called and held in Colorado in 2012. The summit brought renowned PCK researchers together to re-examine PCK to address the disparities that existed regarding the construct that developed since it was introduced by Shulman (1986). The meeting allowed the researchers to share their insights and conceptions of PCK which Gess-Newsome (2015) merged into a model which came to be known as "the 2012 consensus model of PCK" (see Figure 2.2). The model describes teachers' professional knowledge and skills (TPK&S), including PCK, as well as the influence of the PCK on learners' outcomes (Gess-Newsome, 2015).

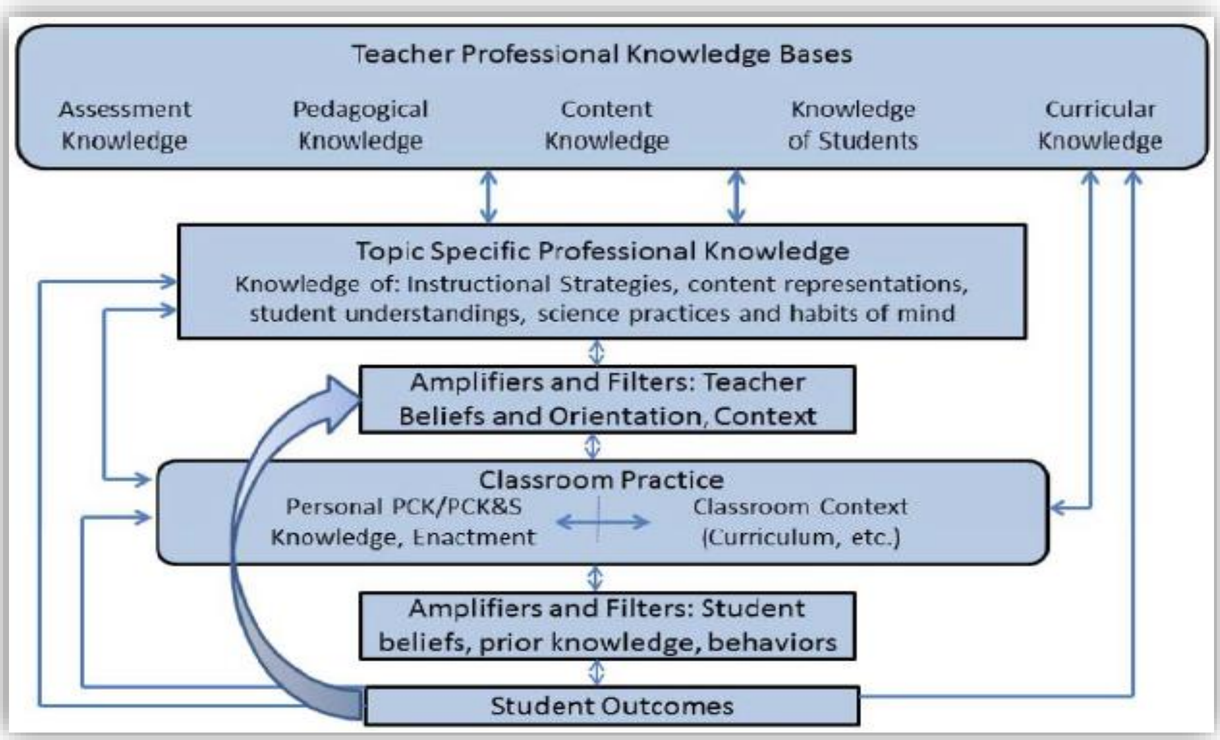



*Figure 2.2: The consensus model of PCK (Gess-Newsome, 2015).*

***An overview of the consensus model***

The first box describes teacher professional knowledge bases (TPKB) that are generic to the teaching profession. These knowledge bases inform and are equally informed by the next level of teacher knowledge, the topic-specific professional knowledge (TSPK). TSPK refers to the knowledge that is tailored for specific topics under the assumption that the transformation of content for instruction occurs at the topic level (Mavhunga & Rollnick, 2013; Veal & MaKinster, 1999). TPKB and TSPK represent canonical knowledge that teachers personalise through amplifiers and filters that are described in the third box from the top in the model. Once personalised, the knowledge becomes “personal PCK” when it is in its static form and “PCK & Skill” when it is enacted during actual teaching. The model recognises the common research finding that learners’ outcomes are not an automatic product of classroom instruction (Fenstermacher & Richardson, 2005; Wayne & Youngs, 2003). Thus, classroom instructions affect learners’ outcomes through learner amplifiers and filters as shown by the last box in the model.

***Detailed description of the components***

The TPKB describes the generic knowledge needed for the teaching profession. It includes (but is not limited to) teachers’ knowledge of assessment, knowledge of learners, content knowledge, curricular knowledge, and pedagogical knowledge (Hashweh, 2005; Rollnick et al., 2008). How TPKB and TSPK inform each other is not clarified apart from the indication that the power of TPKB is in their application to teaching a topic (Gess-Newsome, 2015). Because TSPK is topic-specific, it is characterised by aspects of teacher knowledge that are specific to particular topics as opposed to the generic teaching profession. These aspects include the organisation of concepts, the selection of powerful examples, awareness of learners’ difficulties and misconceptions, instructional strategies, representations as well as the nature of science within a topic (Gess-Newsome, 2015). These two areas of knowledge (TPKB and TSPK) are canonical, which implies that they have common indicators of quality and that they are easily accessible (Rollnick, 2017; Smith & Banilower, 2015).

Upon accessing canonical PCK through various means, teachers personalise it through their own lenses known as amplifiers and filters (Gess-Newsome, 2015). These include teachers’ beliefs about the goals of teaching and schooling, their orientations towards preferred instructional strategies and organisation of the content and their prior knowledge of teaching and contextual variables (Gess-Newsome, 2015). A teacher who believes that teaching is about “telling” would teach using mostly direct instruction while teachers with a “guided inquiry” orientation will initiate activities that channel learners into finding solutions to problems stipulated in the activities (Magnusson et al., 1999). Evidence of the impact of amplifiers and filters is seen in the practice of teachers after they have formally acquired canonical knowledge through attending a teacher professional development workshop. From the information shared in the workshop, teachers can decide to incorporate aspects that are useful and filter those that are less productive (Gess-Newsome, 2015). The resulting knowledge that emerges from the amplifiers and filters is known as “Personal PCK” (Hashweh, 2005) and “Personal PCK and Skill” (Gess-Newsome, 2015). The former refers to the static knowledge used to plan for classroom instruction, while the latter refers to the enactment of dynamic and tacit knowledge in actual teaching (Park & Oliver, 2008a). As shown in the model, the planning and the enactment of knowledge is also influenced by the specific classroom context in which the teachers are operating, for example, the availability of teaching and learning materials (Rollnick et al., 2008).

The consensus model acknowledges the fact that classroom instruction does not automatically result in effective learning (Wayne & Youngs, 2003). Although teachers are regarded as the central figures that shapes learning (Akiba, LeTendre, & Scribner, 2007), it is ultimately the learners that choose to engage with the learning process (Gess-Newsome, 2015). The factors that influence learners’ willingness to engage with content are termed “learner amplifiers and filters”. These factors range from socio-economic statuses to the cognitive abilities of the learners. Not only do learner amplifiers and filters determine learning, they also act as factors that enhance or distort classroom instructions. For example, learners’ interest and willingness to learn can motivate teachers to improve their practice (Keller, Neumann, & Fischer, 2017). However, a disruptive class can lead teachers to using direct instruction to transmit raw concepts without transforming them into teachable forms (Gess-Newsome, 2015).

### 2.3.4 The refined consensus model of PCK

Soon after the consensus model was developed, researchers started finding limitations in it, particularly the lack of detail about PCK (Carlson & Daehler, 2019).

The limitations necessitated modifications in the model to produce the refined consensus model (RCM) of PCK (see Figure 2.3).

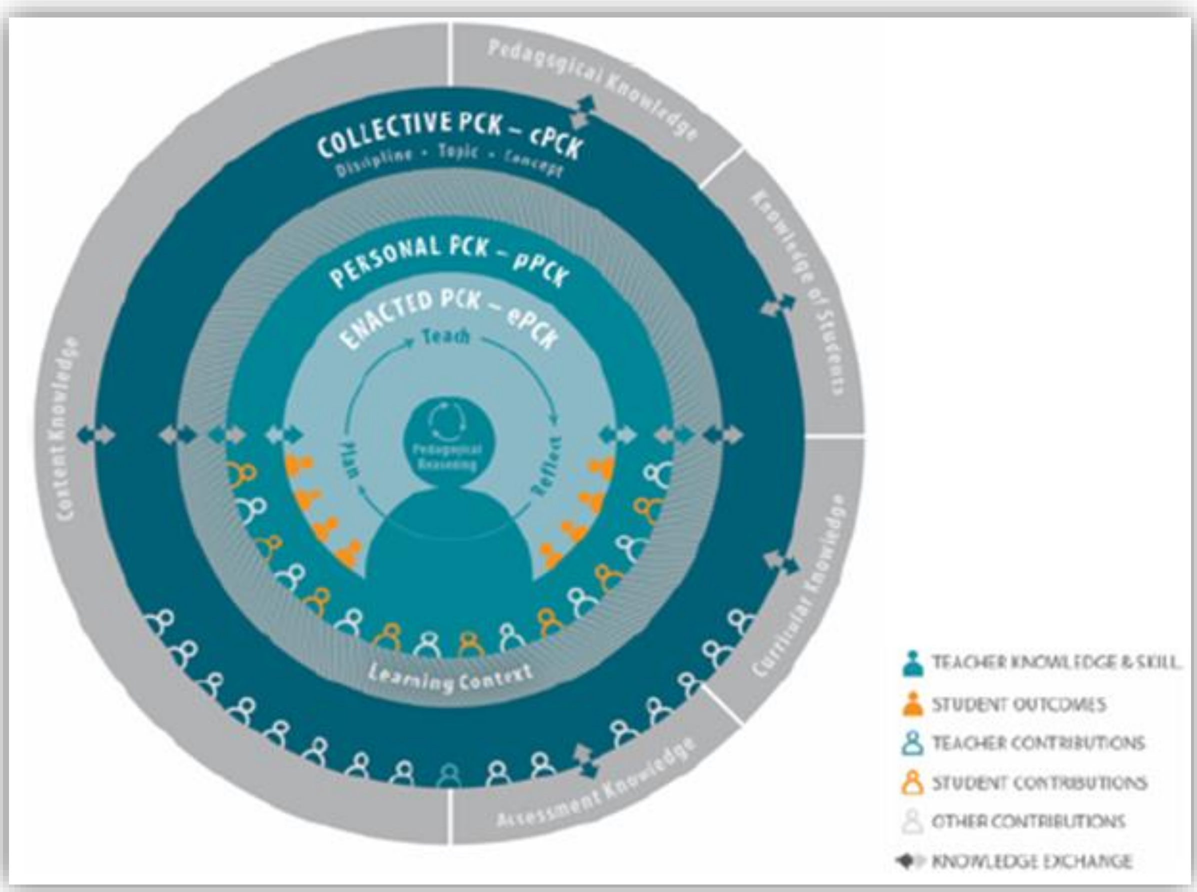



*Figure 2.3: the refined consensus model of PCK (Carlson & Daehler, 2019).*

***An overview of the refined consensus model***

The RCM was not meant to replace the consensus model but rather to improve it. It is thus not surprising that some elements of the two models are the same. Similar to the consensus model, the RCM recognises the broader professional knowledge bases and makes it explicit that content knowledge plays a significant role in teaching. The RCM also recognises amplifiers and filters, shown by the double arrows that demonstrate pathways for “knowledge exchanges” between the different forms of knowledge and realms of PCK shown by the adjacent circles. Furthermore, the RCM recognises the existence of knowledge that is shared by the teaching profession, which is termed collective PCK (cPCK). Different from canonical PCK (Smith & Banilower, 2015), cPCK represents a continuum of common knowledge that extends beyond the information that is publicly available (Park, 2019). It recognises that knowledge may be shared in small settings, for example, between teachers working within the same school, which Carlson and Daehler (2019) termed “local cPCK”. Furthermore, cPCK represents static and context-free knowledge that is similar to what Park and Suh (2015) termed ‘idiosyncratic PCK’. In addition to the consensus model, the RCM recognises that specialised knowledge does not only exist at topic level but also at the domain and concept specific levels. Although these levels are only shown in the cPCK realm due to space constraints, they are applicable across the realms of teacher knowledge (Carlson & Daehler, 2019).

It is evident in the RCM that while several factors amplify and/or filter teachers’ knowledge, the learning context is regarded as a major factor that shapes teachers’ personal knowledge (Carlson & Daehler, 2019). In the explanatory text of the model, Carlson and Daehler (2019) made it explicit that they regard learner attributes as the key element of the learning context of which teachers must be aware. The attributes include age, grade level, dispositions, prior experiences, developmental readiness, language proficiency and cultural beliefs. Once the cPCK has been amplified and/or filtered by an individual, it transforms into personal PCK (pPCK). Personal PCK describes teachers’ unique knowledge and skills that represent their teaching and learning experiences (Hashweh, 2005). As shown in the model, cPCK and pPCK shape each other through the learning context as well as through sharing, articulation and communication of personal knowledge. In the words of Park (2019), cPCK basically represents a collection of pPCK about a specific domain, topic or concept shared by a community of teachers.

Personal PCK serves as a teacher’s personal reservoir of knowledge and skills from which they can draw upon for the purpose of teaching (Carlson & Daehler, 2019). It is seemingly difficult to ascertain the quality of teachers’ personal PCK because it is internal. However, it can be estimated by evaluating the knowledge that they portray during planning, teaching and reflections (Park, 2019). This portrayed knowledge is known as enacted PCK (ePCK) and is regarded as a subset of pPCK (Mavhunga, 2019; Park, 2019). While the model shows that there are knowledge exchanges between pPCK and ePCK, Alonzo, Berry, and Nilsson (2019) have noted that the distinction between these realms of knowledge is hazy, particularly in their tacit forms. Nevertheless, it is important to discuss scholars’ interpretations of the knowledge exchanges between the two realms. When a teacher is involved in a specific lesson, whether during planning, teaching or reflection, they draw upon knowledge from his or her pPCK and amplify or filter it through pedagogical reasoning to make it suitable for that particular moment (Alonzo et al., 2019; Carlson & Daehler, 2019). According to Alonzo et al. (2019), the enactment of PCK occurs in two timescales: the macro and the micro levels of classroom instruction. The macro timescale represents the entire lesson, including the planning and the reflection-on-action, while the micro timescale refers to the distinct moments within the lesson (Alonzo et al., 2019). The scholars have also mentioned that the plan-teach-reflect cycle also exists within the events in a lesson. In this regard, a certain classroom moment would prompt a teacher to reflect (for example noticing a difficulty from learners' questions or responses) and to plan a response (for example asking a follow-up question). Thus, the planning, teaching and reflections that occur during and after a lesson can shape the pPCK of a teacher for future use (Alonzo et al., 2019). The RCM also shows that ePCK has a direct influence on learning outcomes in contrast to the other realms of knowledge, which indirectly influence the outcomes. However, different from the consensus model, the RCM does not indicate how the ePCK shapes learning through the amplifiers and the filters of learning.

## 2.4 THE CONCEPTUAL FRAMEWORK

The conceptual framework that will guide this study is a combination of the refined consensus model of PCK (Carlson & Daehler, 2019) and the TSPCK model (Mavhunga & Rollnick, 2013). The RCM is crucial for this study because it places PCK within a much broader spectrum of teachers' professional knowledge. Furthermore, it describes different realms of PCK; collective, personal and enacted PCK. This present study will be conceptualised within the realms of personal and enacted PCK (see Figure 2.3). The RCM is particularly suitable for this study because it recognises different grain sizes of specialised knowledge for teaching; domain-specific, topic-specific and concept-specific knowledge. As indicated earlier, this study is located at the concept specific grain size of teachers' specialised knowledge. At the time of this study, there was no description of concept specific PCK in the literature. However, Carlson and Daehler (2019, p. 89) have given an example of what the concept specific grainsize of PCK might look like, stating that it can be reflected in the "knowledge of strategies to help middle-grade students understand the concept that matter is neither created or destroyed." In the present study, a concept refers to a well-defined scientific idea, e.g. acceleration is the rate at which velocity changes. Furthermore, concepts are the basic building blocks of topics that may required different knowledge and skills for teaching. Therefore, concept specific PCK refers to the knowledge for teaching specific ideas in a topic.

The RCM also guides the selection of instruments and data that are suitable for reflecting teachers' ePCK, given the complex nature of PCK (Baxter & Lederman, 1999; Park, 2019). As shown in the model, the suitable instruments for capturing ePCK are those that require teachers to plan for a lesson, teach the lesson and reflect on the lesson after delivering it (Park, 2019). Although this study is aimed at exploring PCK at the concept specific grain size, there was no model that described teachers' knowledge in this grain size at the time of the research. As such, teachers' knowledge in each concept of electrostatics will be scrutinised through the components of TSPCK namely; learners' prior knowledge including misconceptions, curricular saliency, what makes the concept difficult to teach, representations including analogies, and teaching strategies (Mavhunga & Rollnick, 2013). PCK components at topic and concept level are compatible yet different in some aspects. I believe that it is curricular saliency in particular that differs in the two grainsizes of PCK. At topic level, curricular saliency refers to the formulation of big ideas, which are the major concepts in a topic (Loughran et al., 2004). Curricular saliency also refers to the understanding of the importance of the topic and how it fits into the curriculum, the sequencing of the big ideas and the explanation of the interrelatedness between the ideas (Rollnick et al., 2008). My conception of curricular saliency at concept level is that it focuses on a single concept at a time, in relation to the other concepts of a particular topic. For example, understanding how a concept of interest builds from corresponding prior knowledge and how it supports learners' understanding of upcoming concepts. Concept specific PCK therefore allows for specificity and organisation of information from which teachers' PCK can be explored. It demands a clear link between a concept of interest and the knowledge components that are used to teach it. For example, the use of a representation has to be linked to a particular concept with a clear description of how the representation supports the teaching of the concept rather than teaching the entire topic.

## 2.5 MEASUREMENT AND ASSESSMENT OF PCK

In this section of the literature review, I will discuss the strategies that researchers have used to access and evaluate PCK from teachers.

### 2.5.1 Accessing PCK

According to Baxter and Lederman (1999, p. 158), “PCK is both an external and internal construct, as it is constituted by what a teacher knows, what he does, and the reasons for the teachers’ actions”. The internal aspect indicates that PCK is private and personal to individuals (Hashweh, 2005). Furthermore, the internal aspect of PCK is difficult to access because it cannot be observed directly (Kagan, 1990). Teachers may share their activities, procedures and insights into teaching, however, they rarely state the reasons behind their choices (Loughran et al., 2004). The reason could be that they are reluctant to share their beliefs (Kagan, 1990), or they lack an awareness of their own PCK (Park & Suh, 2015). Nevertheless, many scholars have used a variety of protocols to collect data that predominantly reflects teachers’ cPCK and pPCK (Alonzo et al., 2019).

Many of the protocols used to access PCK include teachers’ written and spoken accounts of their teaching, and also their actual presentations of lessons. The PCK accessed from teachers’ written accounts of their teaching approaches has been described in many ways including “espoused or planned PCK” (Aydeniz & Kirbulut, 2014), “reported PCK” (Mazibe et al., 2020), “PCK-on-action” (Park & Oliver, 2008a) and “declarative and procedural PCK” (Heller, Daehler, Shinohara & Kaskowitz, 2004). To access this form of PCK, scholars used lesson plans (Geddis & Wood, 1997; Käpylä et al., 2009; Van Der Valk & Broekman, 1999), and pencil and paper topic-specific PCK tests (Mavhunga & Rollnick, 2013). In terms of the RCM, the knowledge captured by these instruments is static and reveals teachers’ cPCK and pPCK as opposed to ePCK, which is PCK in action (Alonzo et al., 2019).

Lesson plans are not particularly common in PCK studies. However, considering the fact that they are “a script of how to perform a classroom session” (Käpylä et al., 2009, p. 1396) consisting of contents, goals and teaching methods, they can be examined and classified into aspects of PCK (Van Der Valk & Broekman, 1999). Geddis and Wood (1997) suggested that whenever lesson plans are used to collect data that reflects PCK, a planning framework needs to be provided for the teachers.

Furthermore, the lesson planning form needs to contain questions that prompt teachers to not only think about content, but also how to unpack it for instructions and the reasons behind their decisions (Geddis & Wood, 1997). With regard to topic-specific PCK tests, scholars have used varieties of assessment items, including multiple-choice surveys (Park et al., 2018; Smith & Banilower, 2015), as well as open-ended questions practice (Kirschner et al., 2016; Mavhunga & Rollnick, 2013). In the study by Smith and Banilower (2015), it was reported that using multiple-choice items to elicit PCK was challenging and unsuccessful. Their instrument presented a misconception as well as numerous possible strategies to address it, of which only two strategies were feasible. The critique against the instrument was that the empirical basis, even for topics with robust literature, was not strong enough to judge the relative effectiveness of different strategies aimed at addressing the same misconception or difficulty (Park et al., 2018). Their items focused on teachers' beliefs or attitudes about teaching strategies rather than their knowledge for teaching. This challenge encouraged Park et al. (2018) to include open-ended questions in their survey, whereby they presented a single teaching strategy for every misconception. Their respondents had two options, either to "agree" or "disagree" with the strategies and to explain why they think the strategy is feasible or describe how they would modify it. Other scholars used open-ended questions, whereby they presented learners' responses which teachers had to scrutinise to identify possible misconceptions and present strategies and representations that they would use to address them (Juttner & Neuhaus, 2012; Kirschner et al., 2016;).

To address the difficulties associated with accessing PCK, Loughran et al. (2004) developed an instrument named a Content Representation (CoRe) tool that captures teachers' PCK by prompting them to articulate it. According to Loughran et al. (2004, p. 376) the tool captures teachers' "main ideas; knowledge of alternative conceptions; insightful ways of testing for understanding; known points of confusion; effective sequencing; and important approaches to the framing of ideas". The CoRe tool was originally developed to capture the holistic knowledge shared by a community of teachers for a specific topic (Loughran et al., 2004). However, it has since been used to capture individual teachers' PCK in specific topics, for example, graphs of motion (Mazibe et al., 2020), semi-conductors (Rollnick, 2017) and electromagnetism (Coetzee, Rollnick, & Gaigher, 2020). When completing the tool as a group or individually, teachers have to firstly identify “big ideas” which they regard as the key concepts in a specific topic (Bertram & Loughran, 2012). The tool then prompts teachers to reveal their conceptions of teaching chosen big ideas (Carpendale & Hume, 2019).

*Table 2.2: A content representation template*

| **Content Area:……………….** | **Key idea A** | **Key idea B** | **Key idea C** |
|---|---|---|---|
| What do you intend learners to learn about this idea? | | | |
| Why is it important for learners to know this? | | | |
| What else do you know about this idea (that you do not intend learners to know yet)? | | | |
| What are the difficulties/limitations connected with teaching this idea? | | | |
| What is your knowledge about learners' thinking that influences your teaching of these ideas? | | | |
| Are there any other factors that influence your teaching of these ideas? | | | |
| What are your teaching procedures (and particular reasons for using these to engage with this idea)? | | | |
| Specific ways of ascertaining learners' understanding or confusion around this idea (include a likely range of responses). | | | |

Sourced from (Loughran et al., 2004).

When developing the CoRe tool, Loughran et al. (2004) did not attach it to a specific model of PCK. As shown in Table 2.2, the tool explores various aspects of teacher knowledge that are found in the models of PCK. Thus researchers have succeeded in capturing teachers' PCK using the tool, regardless of the PCK model that guided their studies. It was Mavhunga and her colleagues (Mavhunga, Ibrahim, Qhobela, & Rollnick, 2016) that adapted the original CoRe tool to align it with the TSPCK model by modifying some of the prompts (see Table 2.3).

*Table 2.3: The adapted CoRe tool (Mavhunga et al., 2016).*

| **Content area** | **Big idea A** | **Big idea B** | **Big idea C** |
|---|---|---|---|
| **A. Curricular saliency** | | | |
| $A_1$. What do you intend learners to know about this idea? | | | |
| $A_2$. Why is it important for learners to know this big idea? | | | |
| $A_3$. What concepts need to be taught before teaching this big idea? | | | |
| $A_4$. What else do you know about this idea (that you do not intend learners to know yet)? | | | |
| **B. What makes a topic easy or difficult to understand** | | | |

| | | | |
|---|---|---|---|
| $B_1$. What do you consider easy or difficult about teaching this idea? | | | |
| **C. Learner prior knowledge** | | | |
| $C_1$. What are learners' typical misconceptions when teaching this idea? | | | |
| **D. Conceptual teaching strategies** | | | |
| $D_1$. What effective teaching strategies would you use to teach this idea? | | | |
| $D_2$. What questions would you consider important to ask in your teaching strategy? | | | |
| **E. Representations** | | | |
| $E_1$. What representations would you use in your teaching strategies? | | | |

Researchers have also captured PCK by observing teachers' lesson presentations. This approach addresses one of the weaknesses of the original PCK construct indicated by Shulman (2015), that is, PCK predominantly focused on teachers' pedagogical minds rather than action. Similarly, Grossman et al. (2009) also criticised the early conceptualisation of PCK for obscuring other important aspects of teaching, especially the skill needed to carry out classroom instruction. Recently, many scholars have advocated the importance of making practice the centre of teacher education (Alonzo et al., 2019; Grossman et al., 2009; Lowenberg-Ball & Forzani, 2009), thus highlighting the need for exploring and developing practice-based PCK (Alonzo & Kim, 2016). In literature, scholars investigated these manifestations of PCK which they described as "PCK-in-action" (Park & Oliver, 2008a), "enacted PCK" (Aydeniz & Kirbulut, 2014; Mazibe et al., 2020) and "dynamic PCK" (Alonzo & Kim, 2016). In terms of the RCM, this knowledge represents a subset of pPCK used in the act of teaching, particularly the dynamic ePCK at the micro timescale (Alonzo et al., 2019). However, limitations regarding PCK captured through lesson observations have been reported in the literature. For example, it is impossible to observe the examples that a teacher decided not to include in the lesson (Baxter & Lederman, 1999). Furthermore, the interpretation of lesson presentations relies on the researcher's inferences (Park & Suh, 2015). It is, therefore, possible to interpret an unfamiliar teaching approach incorrectly and to have fixed expectations of how a topic should be taught (Alonzo & Kim, 2016).

Having said that it is difficult to access teachers' PCK because it cannot be observed directly. Kagan (1990) suggested that it should be accessed indirectly through interviews. The versatility of interviews has allowed researchers to use them to capture different forms of teachers' knowledge. For example, Geddis and Wood (1997) firstly elicited teachers' PCK through lesson plans and later used interviews to explore how the teachers would have eventually presented the lessons (an indication of ePCK). Other scholars adapted CoRe prompts to interview questions (Chordnork & Yuenyong, 2014) to supplement and clarify some of the information that the teachers had written when completing the CoRe tool (Mazibe et al., 2020). It is thus evident that interviews can be used to elicit teachers' cPCK, pPCK and ePCK. With regards to the ePCK in particular, video stimulated recall interviews (Kagan, 1990) enable researchers to elicit teachers' pedagogical reasoning and post-lesson reflections (Park, 2019). Because the reasons behind observable actions are tacit, such interviews allow teachers to describe their internal thoughts that resulted in those actions (Park et al., 2011; Park & Suh, 2015).

### 2.5.2 Assessment of PCK

Smith and Banilower (2015) believe that PCK can be evaluated as adequate or inadequate when judged against set standards, similar to the examination of content knowledge. As such, collective and indispensable PCK (Park & Suh, 2015) can be regarded as the standard of assessment of PCK, considering that it is universal, context-free and that it is shaped by canonical science and learning theories. This standard would indicate the transformation of canonical science by aligning it with learning theories to enhance learners' understanding (Shulman, 1987; Park & Suh, 2015).

To assess the quality of PCK, researchers have used various means of data analysis, including rubrics. By nature, rubrics are used to distinguish categories that reflect the quality of knowledge and skills. In PCK research, rubrics have been used to assess the quality of teachers' static knowledge (Mavhunga & Rollnick, 2013), dynamic knowledge (Alonzo et al., 2012) and the combination of the two (Lee et al., 2007; Park et al., 2011). Furthermore, other rubrics included elements of content (Carpendale & Hume, 2019) and pedagogical knowledge (Kind, 2019). The quality indicators varied from one rubric to the other. Lee et al. (2007) used three categories; limited, basic and proficient while others used four; limited, basic, developing (or proficient) and exemplary (or advanced) (Carpendale & Hume, 2019; Mavhunga & Rollnick, 2013; Park et al., 2011).

Chan, Rollnick, and Gess-Newsome (2019) argued that the existence of many rubrics that differ in many aspects limits communications of research studies among scholars. As such, they developed a universal rubric, named “The Grand Rubric”, which was aligned to the RCM (Chan et al., 2019). Because the rubric is universal, it does not provide the number of categories for the quality of teachers’ knowledge as well as indicators of quality within the categories. Instead, it has aspects of teacher professional knowledge as rows which are as follows: knowledge and skills related to (i) curricular saliency, (ii) conceptual teaching strategies, (iii) learners’ understanding, (iv) component interaction and (v) pedagogical reasoning. When using the rubric, researchers have to choose the number of scoring categories that fit their study as well as the performance indicators within the categories. The number of categories and the performance indicators would inevitably differ across research studies. However, the grand rubric provides a universal structure in which the indicators of quality are accommodated, thus enhancing the communication among scholars.

Because PCK is an amalgam of various knowledge bases, such as knowledge of learners’ thinking and conceptual teaching strategies, researchers have explored the knowledge bases to estimate its quality. Some researchers investigated PCK by focusing predominantly on individual components (Alonzo & Kim, 2016; Lee et al., 2007; Mazibe et al., 2020) while others emphasised the interaction of the components (Akin & Uzuntiryaki-Kondakci, 2018; Mavhunga, 2018) using in-depth analysis (Park & Oliver, 2008a). Since PCK was introduced in education, many scholars have argued that it extends beyond the sum of its individual components (Abell, 2008; Grossman, 1990). Although researchers may not agree on the components of PCK, they share the same sentiments that the quality of PCK depends on the coherent interaction of the components (De Jong, van Driel & Verloop, 2005; Magnusson et al., 1999). However, while the components of PCK are not mutually exclusive (Park & Oliver, 2008a), exploring them separately is also important because it guides the framing of research protocols that elicit specific information about various aspects of PCK (Abell, 2008). It is the knowledge of various components of PCK as well as the ability to integrate them for instruction that yields effective teaching (Abell, 2008; Magnusson et al., 1999). During actual teaching, the synthesis is important because it enables teachers to make on-the-spot decisions when they encounter an unfamiliar teaching situation (Chan & Yung, 2015).

Several researchers have responded to the call for exploring the nature of the interaction of PCK components. Park and Chen (2012) studied the interaction of general PCK components in a quantitative manner using the pentagon model of PCK (Park & Oliver, 2008a). They extracted what they termed "PCK episodes" which are teaching segments that are characterised by two or more components of PCK. They focused on the frequency of component interactions in two biology topics; photosynthesis and heredity. Aydin and Boz (2013) extended the work of Park and Chen (2012) by not only investigating the frequency of interaction but also the strength of the interactions using the Magnusson et al. (1999) model. They developed a rubric that distinguished the strengths of component interaction in two topics (redox reactions and electrochemical cells) on a three-point scale. Both studies reported that component interaction was idiosyncratic and topic-specific. Furthermore, there were variations in the frequency of component interaction as well as the strength of the interactions (Aydin & Boz, 2013). Knowledge of instructional strategies (Aydin & Boz, 2013) as well as student understanding, was central in the interactions (Park & Chen, 2012). Although knowledge of assessment had few interactions with other components in the study by Aydin and Boz (2013), Park and Chen (2012) found it to be mostly linked with student understanding as well as instructional strategies. In addition to the studies mentioned above, Mavhunga (2018) explored the structural complexity of the interaction of TSPCK components using her own model (Mavhunga & Rollnick, 2013). Different from the preceding studies, Mavhunga (2018) only focused on the static PCK that was displayed by pre-service teachers when they were planning to teach chemical equilibrium. She reported that structural complexities of the TSPCK episodes were either linear, interwoven or a combination of the two. Linear structures referred to a sequence whereby one component is utilised completely before incorporating another. Interwoven structures contained multiple components that connected various explanations, all working together in a complementary manner.

## 2.6 EXPERIENCED AND NOVICE TEACHERS' PCK

Kind (2009a) asserted that the PCK of pre-service teachers is "naturally limited" (p. 182) due to a lack of teaching experience which is considered to be a major source of PCK development (Hashweh, 2005). A teacher's PCK develops when it is put into practice; during planning, teaching and reflection (Magnusson et al., 1999; Schneider & Plasman, 2011). It is, therefore, justifiable to assume that experience provides opportunities for teachers to test their teaching approaches using a trial and error method. The opportunities also expose teachers to a wide range of ideas among learners about specific concepts (van Driel et al., 1998) and enable them to develop effective instructional strategies and representations that address learners' challenges (Kind, 2009a; Nilsson, 2008).

In a study by Lee and Luft (2008), experienced teachers identified and recognised the components of PCK and their integration as the cornerstones of effective teaching (Magnusson et al., 1999). While experienced teachers' beliefs and knowledge bases for teaching are organised in a coherent manner (van Driel et al., 1998), novice teachers display fragmented knowledge (Akin & Uzuntiryaki-Kondakci, 2018). Nilsson (2008) commented that in some teacher education institutions, content and pedagogy are taught separately and at times by different teacher educators. This suggests that although the content and pedagogical knowledge of the pre-service teachers might be adequate, the pre-service teachers may lack the necessary expertise needed to integrate them to adequately transform content for instruction (Nilsson, 2008).

The importance of teaching experience is evident when teachers are teaching outside their areas of specialisation. Pedagogical knowledge guides experienced teachers to sharpen their practice by familiarising themselves with the content (van Driel et al., 1998) and acquiring it from a variety of sources, unlike novices who rely only on textbooks (Mizzi, 2013). Furthermore, when experienced teachers learn new content, they anticipate possible learners' challenges and areas of difficulties associated with learning the content (Childs & McNicholl, 2007) followed by effective strategies and representations that would help learners grasp the content with ease (van Driel et al., 1998).

Much of PCK research has focused on novice teachers to develop their practice. In literature, it has been reported that the PCK of novice teachers is often restricted in comparison to that of their experienced counterparts (Kind, 2009a; Schneider & Plasman, 2011). Although the current study is not focused on exploring the development of teachers' PCK, it is important to understand how PCK develops and the conditions that foster its development. Although classroom teaching experience has been identified as a prerequisite for the development of PCK (van Driel et al., 1998; van Driel et al., 2002), experienced teachers are not necessarily expert teachers particularly if they lack content knowledge (Kind, 2009a). Many scholars have advocated the importance of content knowledge in PCK development (Henze et al., 2008; Kind, 2009a,) and opportunities to convey the content to learners (Magnusson et al., 1999). Furthermore, it is important for teachers to receive guidance from experts while reflecting on their practice (Schneider & Plasman, 2011). Many researchers have developed intervention programmes aimed at deepening the PCK of pre-service (Mavhunga & Rollnick, 2013; van Driel et al., 2002) and in-service teachers (van Driel et al., 1998). According to these researchers, their interventions made significant contributions to the practices of the teachers. The interventions awakened teachers' understanding of PCK as a knowledge base that they are continuously learning in their teaching careers (Kind, 2009a). Furthermore, they prompted teachers to think about the components of PCK, for example, misconceptions about specific topics documented in literature as well as representations and instructional strategies that will address and/or prevent them from arising (Mavhunga, 2018; van Driel et al., 2002).

## 2.7 PCK AND LEARNING OUTCOMES

Several attempts to explore the relationship between teachers' characteristics such as college ratings, test scores, degrees and coursework, and certification status and learners' outcomes have been reported in the literature (Wayne & Youngs, 2003). These reported attempts have shown weak relationships between the characteristics and learners' outcomes (Wayne & Youngs, 2003). Alonzo et al. (2012) argued that the weak relationships might have been caused by the fact that the teacher characteristics were not based on teacher knowledge that influences learning directly, i.e. PCK. Other researchers (e.g. Keller et al., 2017) also investigated other factors that influence learning, for example teachers' beliefs and motivations alongside PCK on learners' outcomes and interest in science. The scholars reported a positive link between the motivations of the teachers and the interests of the learners (Keller et al., 2017). In this study, I acknowledge the fact that learners' outcomes are influenced by a variety of factors. However, I focused explicitly on PCK as it is commonly regarded as the knowledge base that shapes teacher effectiveness (e.g. Eames et al., 2011).

In recent times, researchers have used a variety of approaches to investigate the relationship between teachers' PCK and learners' outcomes. However, some of the approaches were detached from the actual teaching that unfolds in the classrooms

(Alonzo et al., 2012). Hill et al. (2005) investigated the effects of teachers' content knowledge for teaching mathematics (CKT-M) on learner achievement gains. Data reflecting CKT-M was gathered using logbooks and an annual questionnaire. The logbooks required teachers to indicate the time devoted to mathematics instruction, the content covered and the instructional practice. The questionnaires on the other hand focused on other factors affecting teachers' practice, for example, teachers' involvement in professional development workshops. Learners' performance was explored at the beginning and at the end of the academic year in which the study was conducted. Thus, the results were based on the information the teachers shared in the instruments, rather than the knowledge that they enacted during actual teaching. Kanter and Konstantopoulos (2010) on the other hand, provided a 12-week project-based science workshop aimed at enhancing the quality of teachers' CK, PCK and their learners' outcomes. These three variables were assessed before and after the workshop. The researchers explored teachers' PCK from their written accounts of episodes for teaching a specific content area; calorimetry and body systems. They regarded an episode as a written sequence in which teachers described learners' thinking about a specific concept, how the learners were thinking as well as strategies for uncovering and addressing possible misunderstandings. Although these studies reported positive relationships between the distinctive aspects of teachers' knowledge and learners' performance, the element of knowledge enactment in the classroom was compromised. As I have reported in an earlier study (Mazibe et al., 2020), written knowledge is not necessarily a true reflection of the knowledge that ultimately manifests during actual teaching.

Alonzo et al. (2012) also noted the limitation of PCK studies that are detached from the enactment of knowledge during actual teaching. As such, they explored the relationship between teachers' PCK and learners' outcomes using secondary data that included teachers' lessons. The data consisted of videos of actual lessons on optics as well as learners' pre- and post-test results about their understanding of the content and interest in the topic. They selected two specific cases based on the fact that they were predominantly similar, however, the learners' post-test results were significantly different. For example, the teachers were teaching the same topic, in similar schools and had three and four years of teaching experience respectively. The scholars explored teachers' PCK in terms of their flexible use of content, rich use of content and learner-centred use of content. The researchers concluded that the differences in the outcomes of the learners were related to the PCK of their teachers. Walter (2013) explored this relationship at the tertiary level by exploring one lecturer's PCK and non-biology students' knowledge of and acceptance of the theory of macro-evolution. She used classroom observations as well as interviews before and after the course to explore the PCK of the lecturer while pre and post-tests were used to explore the students' knowledge and acceptance of macro-evolution. There was no control group for this study. It was reported that the students' knowledge and the acceptance of macro-evolution increased after the course and this was attributed to the high levels of the lecturer's PCK. While these studies reported positive relationships, others indicated that PCK does not predict learners' outcomes (Gess-Newsome et al., 2017). Variations in the relationships reported in the literature may be caused by the differences in the conceptualisations of PCK and the methodologies that were employed in the studies (Chan & Hume, 2019).

## 2.8 RESEARCH ON THE TOPIC OF ELECTROSTATICS

In this section of the review, I will present literature on the teaching and learning of the topic of electrostatics. Firstly, I will discuss the challenges that learners face in the topic according to local and international reports. I will also discuss various teaching strategies that scholars have suggested and used in their studies to enhance learners' understanding of this topic.

### 2.8.1 Challenges in understanding electrostatics

As indicated earlier, the topic of electrostatics at Grade 11 consists of three distinguishable concepts that reveal different learners' alternative conceptions both locally and internationally. The concepts are electrostatic force, electric field and electric field strength. The discussion of the learner challenges will be as follows. The challenges in the concept of an electrostatic force will be discussed separately while challenges in the electric field and the electric field strength will be combined.

***Difficulties in understanding electrostatic forces***

The challenges that have been reported in the literature include difficulties associated with new concepts as well as the application of prior knowledge. With regard to new knowledge, it has been reported that Coulomb's law is poorly understood by learners both locally and internationally. In particular, it is the inverse square relationship between the electrostatic force and the separation distance between charged particles that has been highlighted as difficult (Ajredini, Izairi, & Zajkov, 2013; Maloney, O'Kuma, Hieggelke, & Heuvelen, 2001). For example, it was reported that some students believed that if the distance between charged particles increases by a factor of three, the electrostatic force between the particles weakens by a third instead of a ninth (Maloney et al., 2001). Furthermore, it has been reported that some learners found it difficult to determine the directions of electrostatic forces because they substituted signs of charges into Coulomb's law. As such, they regarded the sign of the final answer as an indication of the direction of the electrostatic force (DoBE, 2016).

With regard to the application of prior knowledge, various difficulties have been reported. Regarding vectors, it was reported that learners found it difficult to represent electrostatic forces using vector diagrams both locally (DoBE, 2017) and internationally (Saarelainen, Laaksonen and Hirvonen, 2007). Vectors form part of the necessary prior knowledge that learners need to solve problems involving electrostatic forces. In the study by Saarelainen et al. (2007), students were asked to draw a vector diagram showing attractive and repulsive forces exerted by two neighbouring charges on a reference charge. Although the attractive force vector was typically drawn correctly, that of the repulsive force was typically drawn incorrectly, extending from the neighbouring charge and pointing towards the reference charge.

The application of Newton's third law has also proved to be difficult for learners both locally (DoBE, 2015) and internationally (Maloney et al., 2001). In particular, it has been reported that some students believed that bigger charges exert stronger forces on smaller charges (Ajredini et al., 2013; Bohigas & Periago, 2010; Maloney et al., 2001). In the study by Ajredini et al. (2013), students were given hanging spheres that carried unequal charges and requested to draw a diagram that shows the interaction between the spheres. Many of the students drew hanging spheres that did not make the same angle with the horizontal, suggesting that they believed that the spheres exerted unequal forces on each other.

Challenges have also been reported concerning the superposition of electrostatic forces in a straight line and in two dimensions (2D), both locally (DoBE, 2017) and internationally (Saarelainen et al., 2017). In the studies by Maloney et al. (2001) and Saarelainen et al. (2007), their participating students generally understood the direction of the resultant force acting on a reference charge in 2D in a set of three charges. However, when another charge was added in the same plane, they failed to understand its effect on the magnitude and the direction of the original resultant force on the reference charge (Maloney et al., 2001).

***Difficulties in understanding electric fields***

Several challenges have been reported in terms of electric fields in the literature. Generally, the major challenges are associated with (i) understanding the source of an electric field, (ii) representing an electric field using field lines, (iii) interpreting electric field lines and (iv) understanding the relationship between an electric field and the electrostatic force.

It has been reported that students found it difficult to distinguish between a charge that creates an electric field and one that tests the presence of the field at a point of interest (Li & Singh, 2017). In particular, the students associated the electric field at a point with the test charge placed at that point, believing that if the test charge is removed, the electric field ceases to exist (Bohigas & Periago, 2010). According to Li and Singh (2017), this challenge may be caused by formal instruction when learners are taught about the use of a positive test charge to obtain the direction of an electric field at a point. Although other students correctly associated electric fields with their source charges, some of them believed that the electric field has to flow from the source to the test charge through field lines before the two charges can interact (Furio & Guisasola, 1998).

Representing electric fields using field lines has also proved to be challenging both locally (DoBE, 2013; 2014; 2016; 2018) and internationally (Ersoy & Dilber, 2014; Taskin & Yavas, 2019; Tornkvist, Pettersson, & Transtromer, 1993). Several errors in the drawings of electric field patterns have been reported. For example, some of the electric field lines were drawn wavy or bent while others intersected and looped around a single charge. Challenges in terms of the interpretation of electric field lines have also been investigated. According to Taşkın and Yavaş (2019), students believe that electric field lines are real. In the words of Tornkvist et al. (1993, p. 338) “they [students] attach far too much reality to the field lines and often treat them as isolated entities in the Euclidean space, not as a set of curves representing a vectorial property of that space”. As such, they interpret field lines as the path of transmission of electrostatic effects responsible for the interactions between charges (Pocovi & Finley, 2002).

Difficulties have also been reported concerning the electric field as a physical quantity with magnitude and direction. According to Saarelainen et al. (2007), students attributed the electric field strength at a point to an electric field line passing through that point. As such, they believed that the electric field strength remains the same along the same electric field line (Saarelainen et al., 2007). Similarly, Tornkvist et al. (1993) reported that their participating students did not infer the electric field strength at a point from the density of the field lines surrounding that point. The students were given a diagram showing the trajectory of a charge cutting through field lines that were not equally spaced. Their task was to draw vectors showing forces acting on the charge in various points on its trajectory. Some of the students drew vectors of equal lengths, suggesting that they regarded the force and thus the electric field as uniform. Furthermore, they did not associate the density of electric field lines with the magnitude of the source charge (Ersoy & Dilber, 2014; Tornkvist et al., 1993).

The relationship between electric fields and forces has also proven to be difficult for students. Some students believe that charges do not experience forces when they are between adjacent field lines until they are placed on a field line (Bilal & Erol, 2009; Pocovi & Finley, 2002). Furthermore, some believe that the direction of the force on the charge is always similar to that of the electric field (Furio & Guisasola, 1998) and thus all charges, regardless of polarity, move in the direction of the electric field (Bilal & Erol, 2009). In actual fact, negative charges spontaneously move in the opposite direction of the electric field. When formally instructed about this fact, some students accept it under the condition that the charges must be moving slowly (Bilal & Erol, 2009). Tornkvist et al. (1993) explored students' understanding of the relationship between an electric field, the force acting on a charge placed in that field and the resulting trajectory of the charge. In one of the questions, the students were given an unidentified charge placed in a well-defined electric field and asked to draw a vector diagram showing the force acting on the charge. It was evident that some of the students regarded the force vector as being similar to the field line because their vector diagrams were curved, resembling the electric field line (Tornkvist et al., 1993). Subsequently, students also believed that the resulting trajectory of the charge will also resemble the electric field lines (Pocovi & Finley, 2002; Tornkvist et al., 1993).

Challenges associated with the superposition of electric fields have been explored in detail by Li and Singh (2017). According to the researchers, the main cause of this challenge is the inability to distinguish between electric field lines and vectors that represent an electric field at a point (Tornkvist et al., 1993). The scholars, Li and Singh (2017), gave students a diagram that contained a set of charges and various points that were not symmetrically positioned with respect to the distribution of the charges. The students were requested to study the diagram and compare the resultant electric fields at those points. It was found that some of the students believed that the resultant electric field was the same in all the points of interest. According to the researchers, the assumptions of the students were not based on the vector nature of the electric field but rather on their “gut feeling” that the charges somehow compensate for each other (Li & Singh, 2017, p. 8). Some of the students also accounted for the compensation, indicating that while one charge is far from the point of interest, another one is closer. Other students believed that it is only the closest charge to the point of interest contributes to the total electric field at that point (Li & Singh, 2017). When those students were asked to defend their responses, they revealed another misconception. They indicated that charges block the electric fields of other charges which dismisses their contribution to the total electric field at a point (Li & Singh, 2017). The scholars also reported that some students believe that the electric fields of like charges always add up at any point while those of unlike charges always cancel each other out. In an event where a charge was added to a system of other charges, students found it difficult to understand its effect on the magnitude and the direction of the resultant electric field at a point (Garza & Zavala, 2013; Maloney et al., 2001).

### 2.8.2 Teaching electrostatics

According to Senthilkumar, Vimala & Al-Ruqeishi (2014), the invisibility of electric charges and fields is the main reason why individuals find it difficult to conceptualise the topic of electrostatics. Thus Borghi, De Ambrosis and Mscheretti (2007) believe that teachers should help learners visualise these concepts through demonstrations and models that explain invisible phenomena to enable them to understand the topic. The strategies that have been predominantly reported in the literature include guided inquiry teaching (Moynihan, van Kampen, Finlayson, & McLoughlin, 2006), representing concepts through hands-on demonstrations (Ajredini et al., 2013; Borghi et al., 2007), videos (Siegel & Lee, 2001) as well as computer-aided simulations

(Çığrık, & Ergül, 2009; Ersoy & Dilber, 2014; Kocakaya & Gonen, 2010; Senthilkumar et al., 2014).

Ajredini et al. (2013) incorporated hands-on demonstrations to test learners' understanding of Coulomb's law. The scholars used two light neutral metal spheres hanging from light insulating strands, close enough to interact without touching. They kept varying the charges on the spheres by bringing them into contact with either a plastic or glass rod charged using either a woollen or a leather cloth and requested learners to observe the movements of the spheres. Thus, in the performance test, learners were requested to sketch the orientation of the spheres, clearly indicating the angle that each string made with the vertical due to the electrostatic force. The learners were given enough information regarding the rod that was used to charge the sphere to infer the type of charge, the distance between the spheres as well as the comparison of the relative magnitudes of the charges.

In terms of teacher development, Borghi et al. (2007) also used real-life demonstrations to guide pre-service teachers to develop models that could be used to explain macroscopic phenomena. In the first experiment, they used two rods, placing one rod horizontally on top of a stand that allowed it to rotate freely in a horizontal plane when subjected to a force. The other rod was regularly brought closer to the horizontal rod to see how it interacted with it. The scholars kept varying the charges on the rods and requested the pre-service teachers to observe the rotation of the horizontal rod. In another experiment, they hanged light plastic balls covered in metal sheets forming a circle and placed a charged object in the centre of the circle. The plastic balls then moved towards the centre. The third demonstration that they used was an electroscope. Based on the demonstrations and the variations of the charges, pre-service teachers were requested (and guided) to develop microscopic models that could help them explain their macroscopic observations.

Scholars also investigated the impact of using computer-aided simulations on learners' performance and understanding of electrostatics in comparison to other teaching strategies, including traditional teaching methods (Çığrık & Ergül, 2009; Kokacaya & Gonen, 2010), conceptual change text (Ersoy & Dilber, 2014) and real-life experiments (Ajredini et al., 2013). The simulations were used to substitute other learning materials, for example drawings of microscopic models that describe induction (Borghi et al., 2007). However, the advantage of the simulations is that they saved time and enabled learners to view all sides of the microscopic models because they were in 3D (Kocakaya & Gonen, 2010). In the study by Ajredini et al. (2013), it was reported that there was no significant difference in the performance of learners who were taught using either real life demonstrations or simulations. Ersoy and Dilber (2014) reported similar findings concerning the comparison between simulations and conceptual change text. However, significant differences in performance were reported in comparison to traditional teaching methods (Çığrık & Ergül, 2009; Kocakaya & Gonen, 2010). Moreover, the scholars have reported that the different teaching strategies that they administered and explored in their studies did not have a significant influence on the learners' attitudes about learning physics.

Other scholars explored the significance of using simulations alongside real-life demonstrations (Goldberg & Otero, 2003) and real-life phenomena (Shen & Linn, 2011) in learners' understanding of electrostatics. Although the focus was not on comparing the effectiveness of each approach, Goldberg and Otero (2003) reported that laboratory experiments did not develop learners' understanding, unless they also used simulations. Laboratory demonstrations, similar to real-life phenomena, can be used to engage with learners' thinking and understanding. However, they do not provide powerful explanations of atomic-level processes unless they are accompanied by microscopic models (Borghi et al., 2007; Shen & Linn, 2011). Shen and Linn (2011) suggested that when using simulations, teachers should request learners to firstly explain microscopic processes governing observed phenomena, and then test their ideas using the simulation. In this case, the simulation plays a confirmatory role. Otherwise, learners' understanding of phenomena can be fostered by using a simulation followed by real-life experiments that play a confirmatory role (Goldberg & Otero, 2003). So overall, it seems that a combination of approaches is helpful for learners.

## 2.9 CHAPTER SUMMARY

This chapter provided a discussion of the reviewed literature concerning the PCK construct and the topic of electrostatics. In terms of PCK, I outlined the components of the construct that researchers proposed and consolidated to produce models that describe the construct. Furthermore, I selected PCK models that are suitable to serve as the conceptual framework for this study. I included a discussion that focuses on experienced and novice teachers' PCK which has implications for the selection of participants as discussed in the next chapter. I have also reviewed the literature on how researchers have accessed and evaluated PCK, as well as how they related learners' outcomes to teachers' PCK. In terms of electrostatics, I reviewed the literature on learners' difficulties in the topic, both locally and internationally. Furthermore, I described strategies that have been recommended by researchers for teaching the topic. In the next chapter, I will discuss the steps that were taken to generate and analyse data that answer the research questions.

# 3. CHAPTER THREE: RESEARCH METHODOLOGY

## 3.1 INTRODUCTION

In this chapter I will outline my justifications for the strategies that I have employed to answer the research questions and subsequently address the research problems discussed in chapter one. I will start by discussing the paradigmatic perspective from which I conceptualised this study, followed by the rationale for the chosen research approach and design. I will then discuss the sampling strategies and the criteria that I used to select participants, which will be followed by a discussion of the strategies that I used to collect the data and an outline of the approaches that I used to analyse the data. Finally, I discuss the necessary measures that were taken to ensure that the findings of this study are valid and trustworthy.

## 3.2 PARADIGMATIC PERSPECTIVE

A paradigm is described as a general perspective or way of thinking that reflects fundamental beliefs, assumptions, concepts, values and practices held by a community of researchers (Johnson & Christensen, 2012; Denzin & Lincoln, 2011). As such, paradigms play a guiding role into the selection of a research approach, i.e. how a research study should be conducted (Tashakkori & Teddlie, 2010) based on their distinctive ontology, epistemology and methodology (Denzin & Lincoln, 2011). Ontology refers to the nature of reality and the truth, whereas epistemology refers to the theory of knowledge and its justification (Denzin & Lincoln, 2011).

This study followed a dialectical pragmatic perspective (Johnson & Christensen, 2012) for its ontological, epistemological and methodological flexibility (Tashakkori & Teddlie, 2010). The nature of dialectical pragmatism promotes the integration of multiple paradigms and interdisciplinary perspectives to address research problems (Johnson & Christensen, 2012). Furthermore, using multiple paradigms contributes to a better understanding of the phenomena under scrutiny (Tashakorie & Teddlie, 2010). As such, I drew heavily from the interpretivist and the postpositivist perspectives to address the research problem that necessitated this study.

The ontology of the interpretivist paradigm holds that reality is relative, that is, it is local, specific, and it is constructed socially and experientially (Guba, 1990). The relative nature of reality indicates that the epistemology of the interpretive paradigm is subjective because knowledge is constructed relative to the researcher's beliefs, opinions, and experiences (Denzin & Lincoln, 2011). The interpretive paradigmatic perspective was particularly important in the investigation of teachers' concept-specific PCK. The ontology of the postpositivist paradigm, on the other hand, holds that there is a single reality that can never be fully understood because of hidden variables and a lack of absolutes in nature (Denzin & Lincoln, 2011). A single reality indicates an objective epistemology, that is, post-positivists observe and measure phenomena to estimate the reality. This paradigmatic perspective guided the investigation of the relationship between teachers' PCK and learners' outcomes in specific concepts of electrostatics.

## 3.3 RESEARCH APPROACH

The primary aim of this study was to investigate the relationship between teachers' PCK and learners' outcomes by focusing on specific concepts of the topic of electrostatics. The paradigmatic perspective from which this study was conceptualised, pragmatism, serves as a philosophical stance for mixed-method research approaches (Tashakkori & Teddlie, 2010). Thus, this study was conducted using a mixed-method research approach where both qualitative and quantitative strategies were combined to generate the necessary data (Gay, Mills & Airasian, 2009). Specifically, the study followed a qual/quan research approach, where the dominant qualitative research techniques were complemented by quantitative ones (Creswell, 2014).

In this study, neither a qualitative nor a quantitative study alone would have sufficiently addressed the research problem in isolation (Creswell, 2014). It was, therefore, necessary to combine qualitative and quantitative approaches to ensure that the weaknesses of one method were addressed by the strengths of the other (McMillan & Schumacher, 2010). Qualitative approaches are suitable for in-depth analysis of the behaviour of individuals in natural settings without generalising the findings (Le Bow et al., 2012). For this study, in particular, qualitative strategies were essential when studying the practice of individual teachers in terms of PCK. Quantitative approaches, on the other hand, rely on statistical inferences and can be used to study large groups of individuals, hence they were important for exploring learners' outcomes.

### 3.3.1 Qualitative research approach

Literature shows that many PCK studies have been conducted using qualitative research approaches (Aydin & Boz, 2013; Baxter & Lederman, 1999; Chan & Hume, 2019). In essence, qualitative research strives to understand real-world behaviour as it occurs naturally from participants' point of view in their own contexts, without manipulating it (Ary, Jacobs, Razavieh & Sorensen, 2006). This is important for PCK studies, because PCK can be personal, private (Hashweh, 2005) and unique to individuals (Cochran et al., 1991). As such, it should be explored using a research strategy that does not believe in a stable, coherent uniform world (Gay et al., 2009), but one that believes that meaning is situated in particular perspectives and contexts.

In this study, teachers' PCK was accessed using a CoRe tool, classroom observations and post-lesson interviews. A CoRe tool is an instrument that enables teachers to write down their knowledge of teaching in a summarised form (Loughran et al., 2004), and as such, it reflects teachers' knowledge portrayed in planning for instruction in a specific classroom context (Gess-Newsome, 2015). The CoRe tool was used to access the personal PCK of the teachers which is described in the RCM (Carlson & Daehler, 2019). I have also explored teachers' PCK using classroom observations, necessitated by an earlier finding that personal PCK is not necessarily a true reflection of enacted PCK (Mazibe et al., 2020). In this regard, the observations were used to access the enacted PCK of the teachers which is described in the RCM. The teachers were then interviewed a few days after they had completed teaching electrostatics. Stimulated recall interviews (Kagan, 1990), also known as think-aloud interviews (Park & Suh, 2015) were used to enable teachers to describe their thoughts that resulted in observable external pedagogical actions through reviewing their video-recorded lessons. These thoughts are described as pedagogical reasons in the RCM (Carlson & Daehler, 2019).

### 3.3.2 Quantitative research approach

According to Ary et al. (2006), quantitative research strategies identify variables to be studied and express them numerically using a set of rules. In this study, although the data reflecting teachers' PCK was explored using qualitative methods, it was converted into numerical data using two rubrics, one for personal PCK (Appendix ii) and the other for enacted PCK (Appendix iii). The rubrics quantify teachers' PCK into levels of competence on a four-point scale (Mavhunga et al., 2013; Park et al., 2011).

As mentioned earlier, quantitative approaches were employed to complement the dominant qualitative research approaches. The quantitative scores that was assigned to the PCK of the teachers represented the quality of the PCK after it was analysed using qualitative methods.

Learners' performance was explored quantitatively as scores in a classroom test on electrostatics. The test questions were based on the same key ideas that were used to explore teachers' concept-specific PCK. Thus in the analysis of the data, learners' performance was averaged per key idea according to the test questions that explored specific concepts of electrostatics. A Pearson's correlation, r, was then calculated to determine the strength and the direction of the relationship between teachers' PCK and learners' outcomes for each key idea. P-values were also calculated for each key idea to determine the level of significance for each relationship.

## 3.4 RESEARCH DESIGN

The nature and the aim of this study necessitated a mixed-method research design in pursuit of knowledge whereby a multiple case study research design was complemented by a non-experimental (ex-post facto) causal-comparative research design (de Vos, Delport, Fouche, & Strydom, 2011).

### 3.4.1 Case study research design

The importance of a case study research design is that it focuses on a single unit of analysis or a bounded system (Gay et al., 2009) to arrive at a holistic understanding and description of the entity (Ary et al., 2006). This study adopted a collective, multiple or multisite case study research design (McMillan & Schumacher, 2010) consisting of four independent cases where each unit of analysis comprised of a teacher and his/her Grade 11 learners.

A multiple case study research design is suitable for mixed-method research (McMillan & Schumacher, 2010), which is the research strategy that this study adopted. This design also conforms to the practices of pragmatists (Johnson & Christensen, 2012) where multiple strategies are used to collect and analyse data (Maree, 2010). The complex nature of PCK demands that the construct must be investigated using a variety of instruments and strategies (Baxter & Lederman, 1999); hence a case study research design was important in this regard.

### 3.4.1 Ex-post facto design

An ex-post facto research design was necessary for this study because it was a non-experimental investigation of the relationship between teachers' PCK and learners' outcomes in the topic of electrostatics. Being used in a mixed methods research, alongside a multi-case study, requires that the natural situation is investigated. Therefore it would not be appropriate to conduct an experiment by manipulating variables, the PCK of the teachers and the performance of the learners (Ary et al., 2006; Graziano & Raulin, 2004; McMillan & Schumacher, 2010). The present study aimed to investigate the influence of teachers' PCK on learners' outcomes without interfering in any way. Each classroom, comprising of a teacher and learners, was regarded as a single case and as such, the relationship between teachers' PCK and learners' performance was limited to the cases of this study.

Although the non-experimental design was useful in this study, it has limitations that had to be addressed to ensure that the results are trustworthy. Firstly, scholars have indicated that it could be challenging to establish the temporal order of variables to determine the cause and the effect between the dependent and the independent variables (Johnson & Christensen, 2012). However, in the case of this study, it is reasonable to assume that if a relationship exists between teachers' PCK and learners' performance, then it must be the PCK that influenced the performance and not the other way around. Secondly, a relationship between variables doesn't necessarily indicate a cause and an effect (McMillan & Schumacher, 2010). Emerging outcomes could also be caused by factors and variables that are excluded or not identified in the research. As mentioned earlier, teachers' practice is not the only factor influencing learners' outcomes. It was, therefore, important to control other factors that could have influenced the performance of the learners to avoid weak conclusions (de Vos et al., 2011; Johnson & Christensen, 2012). Therefore, I attempted to carefully select schools that did not vary considerably from one another in terms of contextual factors. However, I came across challenges. The pre-service teachers chose their hosting schools at free will and as such, one of them practiced in a school that was contextually different from the others. Furthermore, the number of learners in each class was different even for the schools that were contextually similar. Secondly, I administered a baseline test exploring learners' knowledge of electrostatic concepts taught in their previous grade before they were taught new electrostatic concepts in Grade 11. The purpose of the baseline test was to examine whether learners were able to remember some of the concepts of electrostatics that are taught in the previous grade. However, the test was not used in the analysis of the relationship between teachers' PCK and learners' performance.

## 3.5 STUDY VARIABLES

As recommended by Baxter and Lederman (1999), teachers' PCK was explored using a variety of sources. As such, both manifestations of PCK (personal and enacted PCK) were explored and related to learners' outcomes. The nature of the variables was based on the assumption that teachers' practice influences learners' outcomes and not the other way around. As such, teachers' PCK was regarded as the independent variable while learners' outcomes constituted the dependent variable.

*Table 3.1: The variables that are investigated in the current study.*

| Type of variable | Variable |
|---|---|
| Independent variable | Teachers' PCK |
| Dependent variables | Learners' outcomes or performance |

## 3.6 SAMPLING PROCEDURE AND SELECTION OF PARTICIPANTS

Given the nature of the present study, it was necessary to invite Grade 11 physical science teachers and learners as participants. As indicated earlier, the study focused on the concepts of electrostatics that are taught in Grade 11 in the physical science subject. The scheduling of the topic of electrostatics in the grade coincided with the teaching practice internship for pre-service teachers enrolled in a teacher training institution in South Africa. This meant that pre-service teachers that taught physical science at Grade 11 could also participate in the study and were therefore invited. The decision to invite pre-service teachers was driven by research evidence that has shown that PCK develops with teaching experience and as such, pre-service teachers usually lack it (Kind, 2009a; Magnusson et al., 1999). Given the nature of the present study, it was important to have a sample of teachers with a wide range of PCK to investigate their influence on learners' outcomes. The participating in-service and pre-service teachers were in different schools and worked independently from each other to avoid data contamination.

The sampling strategies that I used to select participants were purposive and convenience sampling. Purposive sampling is used to select participants that meet predetermined criteria (Maree, 2010). In the present study, participants were invited to participate if they were teaching physical science at Grade 11 as either in-service or pre-service teachers. Convenience sampling, on the other hand is used to invite individuals that are readily available and accessible to the researcher (Maree, 2010). As a teacher educator, one of my duties was to assess the practice of 4th year B.Ed. students in a real classroom setting during the teaching practice internship. For convenience, I invited the five Grade 11 physical science pre-service teachers that were under my mentorship during the teaching practice internship. Only two of the five pre-service teachers were willing to participate in the study. This sampling strategy was also used to invite two Grade 11 in-service physical science teachers that were teaching in my vicinity. However, one of the invited in-service teachers withdrew from the study the day before data collection from her class. As a result, I invited another teacher who had, unfortunately, started teaching the topic of electrostatics. Learners, on the other hand, were invited to participate only after their teachers had consented to be the participants in the study. The biographical information of the four teachers is summarised in Table 3.2 below.

*Table 3.2: Participating teachers' biographical information.*

| **Pre-service teachers** | | | | **In-service teachers** | | | |
|---|---|---|---|---|---|---|---|
| **Name** | **Age** | **Matric year** | **Type of school** | **Name** | **Highest qualification** | **Teaching experience** | **Type of school** |
| Ms VK | 23 | 2013 | Adequately resourced | Ms SH | NDip: Analytical chemistry<br>Postgraduate certificate in education (PGCE) | Five years | Poorly resourced |
| Mr JM | 24 | 2013 | Poorly resourced | Mr PM | BSc Hons (Chemistry)<br>Postgraduate certificate in education (PGCE) | Ten years | Poorly resourced |

Although the intention was to select schools with similar contexts, the pre-service teachers selected their hosting schools freely. As such, Ms VK taught in a city school while the other participants taught in a township located outside the same city. The number of learners taught by the selected teachers was as follows; 50 for Ms VK, 23 for Mr JM and Ms SH, and 38 for Mr PM. Ms VK taught two classes of 25 learners each.

Just before the semester of teaching practice began, I held discussions with non-participating in-service teachers that served as mentors for the participating pre-service teachers. The discussions aimed to explain the nature of the current study and request permission for the following arrangements. Firstly, the mentors were requested to let their learners write the baseline test exploring their knowledge of Grade 10 concepts of electrostatics. Secondly, they were requested to allow the pre-service teachers to teach the whole topic of electrostatics without interfering during actual teaching. However, they were allowed to give feedback, guidance and recommendations before and after the lessons. Lastly, the teachers were requested to let their learners write a Grade 11 performance test on electrostatics exploring their understanding of the concepts that have just been taught by the pre-service teachers. Similarly, the learners of the participating in-service teachers wrote a baseline and a performance test on electrostatics before and after they were taught the topic, respectively.

## 3.7 DATA COLLECTION INSTRUMENTS

Guided by the aim of this study, I adapted and refined existing instruments to collect data that reflects teachers' PCK and learners' outcomes in electrostatics. In the next sub-sections, I will describe the outline, purpose and importance of each of the instruments that I have used to collect the necessary data for this study.

### 3.7.1 Content Representation (CoRe) tool

PCK is both an internal and external construct, and as such, a part of it is tacit and therefore difficult to capture (Loughran et al., 2004). Nevertheless, scholars have inferred PCK from many sources, including teachers' written accounts of their own teaching. Loughran et al. (2004) introduced a Content Representation (CoRe) tool which is suitable for capturing teachers' personal PCK. When completing the tool, teachers are required to provide big ideas which they regard as the major concepts in the topic of interest (Loughran et al., 2004; Padilla, Ponce-de-León, Rembado, & Garritz, 2008). Next, for each big idea, they have to respond to eight prompts that require them to reflect and reason (Mavhunga & Rollnick, 2013) about teaching the chosen big ideas. In this study, the term “key idea” is used instead of “big idea”. The explanation for this change will be provided in Table 3.6.

*Table 3.3: The original CoRe tool template by Loughran et al. (2004)*

| **Content Area:……………….** | **Key idea A** | **Key idea B** | **Key idea C** |
|---|---|---|---|
| What do you intend the learners to learn about this idea? | | | |
| Why is it important for learners to know this? | | | |
| What else do you know about this idea (that you do not intend learners to know yet)? | | | |
| What are the difficulties/limitations connected with teaching this idea? | | | |
| What is your knowledge about learners’ thinking that influences your teaching of these ideas? | | | |
| Are there any other factors that influence your teaching of these ideas? | | | |
| What are your teaching procedures (and particular reasons for using these to engage with this idea)? | | | |
| Specific ways of ascertaining learners’ understanding or confusion around this idea (include a likely range of responses). | | | |

It has been argued in PCK literature that teachers’ formulation of key ideas is one of the indicators of their PCK because this reveals their understanding the significance of concepts in a topic (Loughran et al., 2004; Mavhunga & Rollnick, 2013). Differently, in this study, the teachers were not required to formulate key ideas of electrostatics as the research problem required PCK to be investigated at the concept specific level. Therefore, key ideas were provided to them to ensure that their PCK was explored based on the same concepts. These key ideas were based on the curriculum and formulated with the help of two physics education experts. Table 3.4 shows the content, concepts and skills that have to be acquired in the topic of electrostatics in Grade 11 as stipulated in the curriculum (p. 84) as well as the corresponding key ideas formulated for the current study.

*Table 3.4: Electrostatics content, concepts, skills and formulated key ideas.*

| | Content, concepts and skills from the curriculum | Key ideas formulated for this study |
|---|---|---|
| Coulomb's law | • State the law and represent it mathematically as $F = k\frac{Q_1Q_2}{r^2}$<br>• Calculate the force exerted on an object by one or more charges in one and two dimensions. | • The force of interaction between two charged objects, its relation to the magnitudes of, and the distance between the centres of the charges. |
| Electric field | • Describe an electric field as the region of space where an electric charge experiences an electrostatic force.<br>• Describe the direction of the electric field as the direction that a positive test charge (+1C) would move if placed at that point.<br>• Draw electric field lines for various configurations of charges. | • The representation of an electric field around a charged object. |
| | • Define the electric field strength at a point as the force per unit charge at that point, $E = \frac{F}{q}$ whereby E and F are vectors.<br>• Deduce $E = k\frac{Q}{r^2}$ to calculate the electric field at a point due to a number of charges. | • Electric field as a physical quantity. |

In this study, I adapted the CoRe tool similar to Mavhunga and colleagues (Mavhunga et al., 2016) so that it targets information that is directly related to the components of PCK chosen for this study. The reasons for the adaptations are discussed below.

In the adapted CoRe tool, the word “students” was replaced with “learners” because, in the South African context, learners are pupils attending primary or secondary school level whereas students attend tertiary institutions. Pre-service teachers are regarded as students, and they are often called “student teachers” in many South African schools during the teaching practice internship. Secondly, in the original CoRe tool, there was no clear distinction between teachers’ awareness of learners’ difficulties in their prior knowledge and in the new concepts that they were about to teach. Hence prompt four and five were changed to distinguish between the necessary pre-concepts that learners must have before learning electrostatics in Grade 11 and difficulties that they are likely to encounter when learning new concepts, including the causes for such difficulties (See Table 3.5). Thirdly, it was also important that the adapted tool contains prompts that explicitly explore teachers' awareness of representations that support the explanations of concepts, how teachers use the representations and the purposes served by each representation. Fourthly, teachers had to be prompted explicitly to reveal their knowledge of strategies that enhanced learners' understanding of each idea, including questions that they would ask learners during teaching. This necessitated changes in prompt seven and eight. Fifthly, prompt six was discarded because the pre-service teachers completed the CoRes during a physics methodology class before they went for teaching practice; thus they did not know the contextual settings of their hosting schools.

*Table 3.5: The adaptation of CoRe prompts for the current study.*

| **Prompts from Loughran et al. (2004)** | **Adapted prompts for this study** |
|---|---|
| What do you intend students to learn about this idea? | What do you intend learners to learn about this idea? |
| Why is it important for students to know this? | Why is it important for learners to know this? |
| What else do you know about this idea (that you do not intend students to know yet)? | What else do you know about this idea (that you do not intend learners to know yet)? |
| What are the difficulties/limitations connected with teaching this idea? | What do learners find difficult to understand about this idea? What causes these difficulties? |
| What is your knowledge about learners' thinking that influences your teaching of these ideas? | What are the necessary pre-concepts that learners must have before teaching this idea? Also include difficulties that they have in the pre-concepts. |
| Are there any other factors that influence your teaching of these ideas? | Removed |
| What are your teaching procedures (and particular reasons for using these to engage with this idea)? | Which representations and analogies would you use to teach this idea how would you use them? Also include the purpose served by each representation. |
| Specific ways of ascertaining students' understanding or confusion around this idea (include a likely range of responses). | Which effective strategies would you use to teach this idea and how? Also include conceptual questions that you would ask learners. |

### 3.7.2 Lesson plans

As indicated in chapter two, some scholars have used lesson plans to gather data that reflect teachers' personal PCK (Geddis & Wood, 1997; Käpylä et al., 2009; Van Der Valk & Broekman, 1999). In this study, the participating teachers were requested to provide their plans for all the lessons that they presented for the study. The nature of the teaching practice internship required pre-service teachers to complete a lesson planning form prescribed by their institution for all the lessons that they presented. The lesson planning form was generic and tailored to suit any subject, topic and age group.

Although the lesson planning form was not structured to reflect the aspects of PCK, some of the information required in the form revealed specific components of the TSPCK framework, as shown in Table 3.6.

*Table 3.6: The links between the prescribed lesson planning form and PCK components.*

| | **Items in the lesson planning form** | **Comments** |
|---|---|---|
| 1. | Subject, type of lesson, date, grade, length of period, number of learners and the topic from CAPS | This section explores general information about the context in which the pre-service teachers are teaching. |
| 2. | Knowledge areas for foundation phase only. | Not applicable in Grade 11. |
| 3. | Integration with other subjects. | This section may reveal the pre-service teachers' knowledge of the curricular saliency. |
| 4.1<br>4.2<br>4.3 | General aims from CAPS<br>Specific aims from CAPS<br>Topics (content, concepts and skills) from CAPS | Pre-service teachers are expected to copy this information as it is from the Curriculum, and thus it does not reveal anything about their knowledge, particularly PCK. |
| 4.4 | Lesson outcomes:<br>Existing knowledge, skills and values that should be in place before the lesson.<br>New knowledge, skills and values after the lesson. | This section reveals pre-service teachers' awareness of the necessary prior knowledge for learners. However, the teachers are not expected to indicate possible difficulties in the prior knowledge. Nevertheless, this section also addresses an aspect of curricular saliency, the concepts that the teacher intends learners to know after the lesson. |
| 4.5 | Brainstorming area for rough planning. | Several components of PCK may be revealed here. |
| 5. | Learning theories as well as teaching strategies and techniques. | This section explores aspects that are general to teaching and not just electrostatics. |
| 6. | Evidence of learning (assessment) | This could reveal conceptual teaching strategies. |
| 7.1<br>7.2<br>7.3<br>7.4 | Theme of the lesson (Big idea)<br>Introduction to the lesson.<br>Development of the lesson.<br>Consolidation of the lesson. | This is why the term "big idea" in the CoRe was changed to "key idea" because it is used in the lesson planning form. This section explores several components of PCK because the actual lesson is outlined here. |
| 8. | Classroom management. | Pedagogical knowledge, not PCK. |
| 9. | Learner enrichment. | Pedagogical knowledge, not PCK. |
| 10. | Learner support. | Pedagogical knowledge, not PCK. |
| 11. | Learning and Teaching Support Materials (LTSM) | Representations that pre-service teachers intend to use to support the discussion of concepts in the lesson. |
| 12. | Bibliography (Harvard method) | Not applicable in the components. |
| 13. | Reflection on the lesson presented. | Knowledge of several components may be shared in this section. |

### 3.7.3 Classroom observations

The classroom environment is important in education because it is the place where PCK is enacted. While exploring teachers' personal PCK is important because it informs lesson planning (Alonzo & Kim, 2016), it does not necessarily reflect the PCK that teachers enact during teaching (Mazibe et al., 2020). Alonzo et al. (2012) explored teachers' enacted PCK using classroom observations under the argument that they "reflect PCK as it is used in practices associated with teaching [and learning], rather than practices that are further removed from the classroom – such as interviews and paper-and-pencil assessments" (p. 1216).

### 3.7.4 Interviews

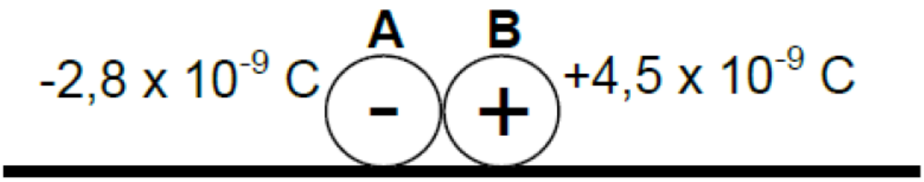
As indicated in chapter two, because PCK is an elusive and tacit construct that cannot be observed directly, Kagan (1990) recommended that it should also be explored indirectly using interviews. Video stimulated recall (VSR) interviews have been advocated as a tool that explores the nature of teachers' pedagogical reasons that underpins their presentations of lessons (Denley & Bishop, 2010). Although classroom observations were the primary data source from which teachers' enacted PCK was inferred, they only revealed external pedagogical actions that were enacted by the participants. The pedagogical reasons that informed the external actions were not visible during teaching and could be uncovered using VSR interviews. Before conducting the VSR interviews, I established a rapport with the teachers as recommended by Denley and Bishop (2010) in an attempt to ensure that the teachers described their thoughts instead of defending their actions.

### 3.7.5 Performance tests

This study was located in the South African context, and as such, the instruments that investigated learners' performance were set relative to the standards of the national assessments. Two tests were designed in this regard. A baseline test explored learners' prior knowledge of electrostatics taught in Grade 10 and the performance test that gauged their understanding of Grade 11 concepts of electrostatics after they had been taught by the participating teachers. Some of the test questions were informed by my personal experience of teaching this topic, while others were adapted from national examinations set by the DoBE and academic literature on this topic (e.g. Maloney et al., 2001). An example of a question from the Grade 10 baseline test is given in Figure 3.1. This question was taken from a previous grade 10 national examination question paper.

**QUESTION 4**

4.1 Two identical metal spheres, **A** and **B**, on an insulated surface carry charges of – 2.8 x $10^{-9}$ C and + 4.5 x $10^{-9}$ C respectively. The spheres are brought into contact with each other.




4.1.1 During contact, are electrons transferred from **A** to **B** or from **B** to **A**? (1)

4.1.2 It is observed that the spheres spontaneously move apart after contact. Briefly explain this observation. (3)

4.1.3 Calculate the new charge on each sphere after they have moved apart. (3)

*Figure 3.1: An excerpt of the baseline test.*

Because the baseline test was meant to explore learners' prior knowledge, I limited it to more conceptual rather than algorithmic questions. The question shown above was formulated to explore learners' prior knowledge that develops into new concepts taught in Grade 11. The first two questions explore learners' understanding of the fact that since metals are good conductors, electrons will be transferred from A to B and that both spheres will therefore bear the same charge resulting in a repulsive force. In Grade 11, learners learn about the intensity of the attractive and the repulsive forces between unlike and like charges, respectively as described by Coulomb's law. Table 3.7 summarises the sources of the questions used in the performance while Figure 3.2 provides an example of the questions.

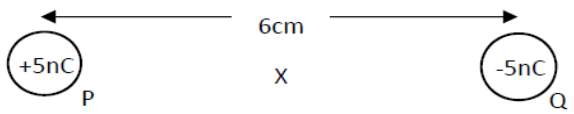
*Table 3.7: The sources for the questions used in the performance test*

| Questions | Source | Key idea |
|---|---|---|
| 1.1 | Maloney et al. (2001) | Electrostatic force |
| 1.2 | Taken from DoBE's previous question papers. | Electrostatic force |
| 1.3 | Maloney et al. (2001) | Electrostatic force |
| 1.4 | Maloney et at. (2001) | Electric field |

| | | |
|---|---|---|
| 1.5 | Maloney et al. (2001) | Electrostatic force |
| 2.1.1 | Taken from DoBE's previous question papers. | Electrostatic force |
| 2.1.2 | Taken from DoBE's previous question papers. | Electrostatic force |
| 2.1.3 | Taken from DoBE's previous question papers. | Electrostatic force |
| 2.1.4 | Taken from DoBE's previous question papers. | Electrostatic force |
| 2.1.5 | Taken from DoBE's previous question papers. | Electrostatic force |
| 3.1.1 | Self developed. | Electric field |
| 3.1.2 | Self developed. | Electric field |
| 3.1.3 | Self developed. | Electric field |
| 3.1.4 | Self developed. | Electric field strength |
| 3.2.1 | Self developed. | Electric field strength |
| 4.1.1 | Taken from DoBE's previous question papers. | Electric field |
| 4.1.2 | Taken from DoBE's previous question papers. | Electric field strength |
| 4.1.3 | Taken from DoBE's previous question papers. | Electric field strength |
| 4.1.4 | Taken from DoBE's previous question papers. | Electric field strength |
| 4.1.5 | Self developed. | Electric field strength |

**QUESTION 4**

4.1 Two small charged particles, P and Q, are placed on a straight line 6 cm apart. The charge on P is +5 nC and the charge on Q is -5 nC. X is a point exactly halfway between the two small charges.




4.1.1 Draw the resulting electric field pattern of the charged particles. (3)

4.1.2 Determine the magnitude and the direction of the electric field at point **X** due to charge **P**. (4)

4.1.3 Determine the magnitude and the direction of the electric field at point **X** due to charge **Q**. (3)

4.1.4 Determine the net electric field at point **X** due to charge **P** and charge **Q**. (2)

4.1.5 Suppose the two spheres were both positive with equal magnitudes, what would be the magnitude of the net electric field at point **X**? Defend your answer. (3)

*Figure 3.2: An excerpt of the performance test.*

This question was developed based on my personal teaching experience. I have observed that learners tend to substitute the signs of charges when calculating the electric field or the electrostatic force. They typically refer to attractive or repulsive without interpreting the directions in terms of Cartesian coordinates. In questions with more than one charge, learners then often fail to determine the resultant field at a specific position correctly. The complete baseline and performance tests are available in Appendix iv and vi, respectively.

## 3.8 DATA GATHERING PROCESS

As indicated earlier, I have adapted and used existing instruments and approaches to collect data that reflect teachers' PCK and learners' outcomes. As such, it was necessary to pilot the instruments to examine whether they measure the constructs for which they were intended.

### 3.8.1 Pilot study

***The adapted CoRe tool***

The adapted CoRe tool was administered to the participating pre-service teachers as an assignment for their methodology module to examine whether the formulated key ideas and the questions were clear and explicit about the information that was intended. Considering the fact I formulated the key ideas and provided them to the participants, I believed I could investigate the teachers' PCK without exploring aspects of curricular saliency. This decision was based on the understanding that the ability to formulate key ideas indicates one's competence in terms of curricular saliency and because the key ideas were predetermined, I thought there was no need to explore teachers' knowledge of curricular saliency. The analysis of the CoRe assignment revealed that this was a bad idea. Firstly, some of the students could not separate learners' prior knowledge from new concepts. They regarded charges, vectors and Newton's third law as ideas that should be taught as new concepts while they regarded Coulomb's law as a pre-concept. Secondly, when asked about the importance of learning each idea, the students indicated specific subsequent concepts towards which each idea develops. However, some of these concepts are taught at the university level, for example, Gauss's law. As a result, the CoRe was revised to include aspects of curricular saliency, and it was formulated to be limited to concepts taught at secondary school.

Some of the prompts were also adapted because the students interpreted them differently. For example, when the students were asked "What is difficult to teach about this idea and why?" they referred to challenges faced by teachers rather than those faced by learners. For example, they indicated that a shortage of teaching equipment and facilities makes it difficult to teach the topic of electrostatics. This prompt was therefore revised and changed to: “What do learners find difficult to learn about this idea and why?” This new formulation ensured that the prompt explicitly refers to teachers’ knowledge of challenges faced by learners and the foundations of such challenges. Once the revised CoRe was ready, it was handed to the pre-service teachers again as an assignment for the methodology module. However, the pre-service teachers were not given feedback on how they had completed the initial CoRe. Nevertheless, I provided guidance on the completion of the revised CoRe, focusing explicitly on the information required by each prompt.

***The baseline and the performance test***

The baseline and the performance tests were piloted with Grade 12 learners from a conveniently chosen non-participating school during winter school holidays (June 2018). As I have indicated earlier, the Grade 12 physical sciences final examination includes concepts of electrostatics that are taught in Grade 10 and 11. Before the study, I personally conducted holiday classes where I helped Grade 12 learners revise the topic of electrostatics and piloted the instruments the same way I had intended to administer them in this study. The Grade 10 baseline test was written before the revision classes commenced, and the Grade 11 performance test was written afterwards. While the learners were writing each test, I took note of the time it took them to complete the tests and the questions on which they needed clarity. It took about 30 minutes and an hour for the learners to complete the baseline and the performance tests, respectively. While marking the tests, I checked whether the questions were clear or ambiguous, based on the responses of the learners and changes were made where necessary.

The pilot results highlighted the importance of using multiple and various types of questions in each concept in the performance test. In particular, they have shown that a valid and reliable indication of learners’ performance in a concept demands the use of multiple questions that focus on different aspects of the same concept. It was for this reason that multiple and different kinds of questions were kept as they were in the performance despite the fact that learners required more time to complete the test because the aim was to get a reliable indication of their performance across the concepts.

### 3.8.2 Current study

***Teachers' personal PCK***

Pre-service teachers completed two CoRe tools that served as assignments for their methodology module. The first assignment aimed to pilot the CoRe tool, which was later administered as the second assignment after the necessary changes had been implemented. Consent was obtained to use the CoRe assignments of the participating pre-service teachers as data for this study. The purpose of using the CoRes as assignments was to encourage the pre-service teachers to share their knowledge to the best of their abilities, given the fact that they contributed towards their final grade for the module. However, it also meant that the CoRes were administered three months before the teaching practice internship commenced. This is considered to be one of the limitations of this study. The pre-service teachers also completed lesson planning forms for all the lessons that they presented during the teaching practice internship as required by the teaching practice office. This means that there were lesson plans for all the lessons that they presented on electrostatics which were collected and analysed to supplement the information shared in the CoRes.

In-service teachers, on the other hand, were also requested to provide their lesson plans for the lessons that they taught. However, they were reluctant, and I did not insist to maintain good relations.  Regarding the CoRes, it was evident that completing the tool was time-consuming for the teachers, and they were reluctant to complete it. One of them returned it a few days after she had completed teaching the topic of electrostatics. The other teacher did not return the CoRe and was also unavailable for an interview to substitute the CoRe. Once again, I did not insist to maintain good relations with the participant.

***Baseline test***

The baseline test was written just before the teachers had started teaching the topic of electrostatics. However, I met one challenge in this regard as one in-service teacher that had already consented to participate, withdrew from the study. I then invited another in-service teacher only to find that she had already started teaching the topic of electrostatics to her Grade 11 learners. Nevertheless, her learners wrote the baseline test before she continued from where she had left off. As predicted by the pilot results, all learners from each school managed to complete the test within their normal learning periods, including those who attended a school with 30 minute periods.

### *Enacted PCK*

According to the curriculum from the DoBE (2011), the topic of electrostatics requires approximately six hours to teach to completion. However, given the differences in the lengths of periods in the schools, the number of lessons that were video recorded varied from one teacher to the next as shown in Table 3.8.

*Table 3.8: The number of lessons observed for each participating teacher*

| Teacher's name | Length of a single period | Number of periods used to teach the fundamental concepts | | |
|---|---|---|---|---|
| | | Electrostatic force | Electric field | Electric field strength |
| Ms VK | 50 minutes | Four (4) | Three (3) | Two (2) |
| Mr JM | 30 minutes | Five (5) | Two (2) | Two (2) |
| Ms SH | 40 minutes | Two (2) | One (1) | One (1) |
| Mr PM | 40 minutes | Four (4) | Two (2) | Two (2) |

Due to time constraints, I was unable to personally video record all the lessons of the participating teachers as some of them were running concurrently. As such, I recruited non-participating pre-service teachers that were practising in the same schools to record some of the lessons. The recruited pre-service teachers were guided on how to record the lessons, for example, capturing from the back of the class and zooming into significant teachers' writings on the board. With regard to the in-service teachers, I personally recorded all their lessons.

All the lessons, including those that were recorded by the non-participating pre-service teachers, were recorded without any interference from the videographers. The teachers were allowed to teach the way they would normally teach this topic in the absence of the videographers. The recordings were only stopped after the teachers had confirmed that they had covered everything that they had planned to teach in this topic. As a teacher educator, my role during lesson observations was to provide feedback and guidance to the pre-service teachers to improve their practice. However, for the purpose of this study, I reserved all my comments until they had completed teaching the topic to limit my influence on their teaching. However, the mentor teachers were not restricted from giving their feedback and comments.

***Performance test***

The fact that the participating learners were going to write a test after completing the topic of electrostatics was not kept a secret. The performance tests were scheduled to take place the day after completing the topic. However, several issues emerged. The pilot study showed that learners required at least an hour to complete writing the test. It was evident that double periods were sufficient for the learners to write the test and complete it because the participating schools had shorter periods. In some of the schools, double periods were not allocated, and, as a result, the learners wrote the test over two days. However, the learners were not told that they would be given the test the following day to complete. This was to ensure that they did not revise the content. However, it is noted that this is another limitation of the study.

***Video stimulated recall interviews***

Given the nature of the study, several lessons were recorded from each participant to explore their PCK across the concepts of electrostatics. Once all the lessons from the teachers were recorded, I repeatedly watched them while noting down the times where noteworthy teaching events took place. These noteworthy events included instances where the teachers probed, revised their explanations, ignored a question or aspect of the key ideas, and instances where they provided incorrect explanations. The noteworthy events, and thus the formulated interview questions varied from one case to the next. For example, if one teacher omitted an aspect that is prescribed in the curriculum, they would be asked to explain the reasons behind omitting the aspect. If another teacher revised his or her explanation, they would be asked to state the reasons behind the change. I could not hold the interviews immediately after the lessons which would have provided the teachers' pedagogical reasons while they still remembered the thoughts that shaped their actions. This was because the teachers had other commitments, for example teaching the next class. During the VSR interviews, I fast-forwarded the clips to the times that I had noted down. The participating teachers were requested to watch the segments and describe their thoughts that shaped the observed pedagogical moves. The teachers were also allowed to defend their actions because some time had elapsed between the lessons and the interview.

## 3.9 DATA ANALYSIS

The nature of this study demanded that a variety of strategies and approaches had to be used to analyse the data that was collected using multiple instruments. As indicated earlier, I collected data that reflected teachers' personal PCK, enacted PCK and learners' performance.

### 3.9.1 Expert CoRe

An expert CoRe tool was developed to serve as an example of exemplary PCK to aid the analysis of the teachers' PCK. I developed the expert CoRe based on my own teaching experiences, which I refined after consulting with my supervisors that were experts in physics education (See Appendix i). To enhance the trustworthiness of the tool, I consulted several sources of information to guide my responses to the CoRe prompts. The sources were the curriculum, academic literature on electrostatics and diagnostic reports from the DoBE based on Grade 12 final examination results. With regards to learners' prior knowledge, the curriculum outlined the prior knowledge that is scheduled before the topic of electrostatics. The academic literature and the diagnostic reports outlined learners' challenges in the prior knowledge. Regarding curricular saliency, the curriculum outlined the concepts that should be taught per key idea. The academic literature and the diagnostic reports were consulted again, this time to explore learners' difficulties in the new concepts of electrostatics taught in Grade 11. The knowledge of representations and analogies emerged mostly from academic literature, while that of conceptual teaching strategies was based on my teaching experience.

The expert CoRe was scrutinised by a teacher educator from another reputable institution in South Africa. He raised a major concern; regarding the concept of electric fields as a prerequisite for that of electrostatic forces, which was opposite to the sequence in the expert CoRe. This was an important concern that he raised and worthy of a response. My argument in this regard is that the concept of the electrostatic forces is not as abstract as that of electric fields and is easier to conceptualise. It is easier to visualise an electrostatic force where two objects can be charged and be allowed to attract or repel. Although an electric field is responsible for this interaction, learners can only accept its existence through an observable phenomenon of a force. In actual fact, the curriculum, as well as science textbooks, also sequence the concepts in the same order, starting with the concept of the electrostatic force before the electric field. Nevertheless, discussing an electric field first could also be successful; hence the expert CoRe is not regarded as being the only way to unpack concepts of electrostatics for instruction.

### 3.9.2 Personal PCK

Personal PCK refers to the knowledge that the participating teachers portrayed in writing in the CoRe tool and the lesson plan. In many PCK studies, data reflecting teachers' personal PCK had been analysed using rubrics (Mavhunga & Rollnick, 2013; Park et al., 2011). For this study, I designed a rubric that assessed teachers' competence in each of the three concepts that were used as key ideas for the study by adapting pre-existing rubrics (Park et al., 2011). A four-point scale (1 = limited, 2 = basic, 3 = developing and 4 = exemplary) was used to indicate the level of competence in each component according to the components of PCK from Mavhunga's model (Mavhunga & Rollnick, 2013). The rubric was generic and therefore applicable in each of the key ideas. Furthermore, it was used in conjunction with the expert CoRe that served as an example of exemplary PCK, so as to contextualise the interpretation within the specific key ideas. This was particularly important because the personal PCK of the teachers was explored and scored within the three key ideas separately. Because data was collected using CoRes and lesson planning forms, I had to integrate it to obtain a holistic score that represents teachers' PCK for each key idea by using the rubric. In this regard I carefully selected pieces of noteworthy information about teaching the concepts. This included practices that are good and those that are inadequate against the expert CoRe and the rubric. For example, if a teacher reports about a representation in one instrument and then goes on to explain how the representation supports the teaching of a concept, then the information would be combined and the teacher would be scored above basic competence. However, if there are extremities in the same component across the instruments, then an aggregate score would be allocated. For example, if a teacher identifies prior knowledge and misconceptions while some of the misconceptions include correct conceptions, then s/he would be allocated a basic score. An excerpt of the personal PCK rubric is reflected in Table 3.9, while the complete rubric is in Appendix ii.

*Table 3.9: An excerpt of the rubric for quantifying teachers' personal PCK for the component, "conceptual teaching strategies".*

| | Limited | Basic | Developing | Exemplary |
|---|---|---|---|---|
| Conceptual teaching strategies | Learners' prior knowledge and areas of conceptual difficulty are not indicated. As such, there are no reported conceptual teaching strategies intended for conceptual change and conceptual development. No indication of how concepts will be sequenced, interrelated and developed through the use of representations. The lesson is highly teacher centred. | There is evidence of strategies intended to uncover and address a single prior concept. There is evidence of strategies intended to uncover and address an area of difficulty in the new concepts. These strategies exclude the use of representations, or the representations do not appear to be effective. The sequencing of concepts is illogical, while the interrelatedness between the concepts is poorly explained. There is evidence of limited learner involvement. | There is evidence of strategies intended to uncover and address two major prior concepts. There is evidence of strategies intended to uncover and address areas of learners' difficulties. These strategies are accompanied by a single representation predominantly aimed at addressing difficulties or supporting new concepts. There is an indication of sequencing and how most of the concepts are interrelated. There is evidence of encouraged learner involvement. | The teacher uncovers all the necessary prior knowledge and identifies the correct conceptions, gaps and difficulties. The teacher confirms correct prior conceptions and addresses gaps and difficulties. The teacher reported more than one representation tailored to address areas of difficulty and to support conceptual development. The sequencing of concepts is logical and included the explanation of the interrelatedness between concepts. Activities are predominantly learner centred. |

### 3.9.3 Enacted PCK

Similar to the strategy used to analyse the data reflecting teachers' personal PCK, a rubric was designed to guide the analysis of the enacted PCK in conjunction with the expert CoRe. The enacted PCK rubric was different from the personal PCK rubric because it assessed teachers' knowledge portrayed during actual teaching, in terms of the topic specific PCK components. With regards to learners' prior knowledge, I examined the pre-concepts that the teachers uncovered, addressed and engaged with during the lesson. In terms of curricular saliency, I evaluated how they sequenced concepts and developed new knowledge of electrostatics from the prior knowledge. I also examined how they presented difficult concepts that they indicated as such in their CoRes, as well as those that I indicated as difficult in the expert CoRe tool. Reference to the expert CoRe was necessitated by the possibility that the teachers may have regarded some prior knowledge as difficult concepts for the learners. With regards to representations, I examined the demonstrations, analogies and examples that they used to support their discussions of both pre-concepts and new knowledge. The fifth component, conceptual teaching strategies, describes teachers' strategic combination of their knowledge of the preceding TSPCK components to effectively engage with a concept as shown in Table 3.10 (Mavhunga & Rollnick, 2013).

*Table 3.10: An excerpt of the rubric used to quantify teachers' enacted PCK.*

| | Limited | Basic | Developing | Exemplary |
|---|---|---|---|---|
| Conceptual teaching strategies | The teacher does not engage with prior knowledge to explore correct conceptions, gaps and difficulties in it. Conceptual strategies tailored for difficulties in the prior knowledge are thus absent in the lesson. The teacher does not facilitate discussions to explore learners' understanding of new concepts. Strategies, for example the use of representations to address areas of learners' difficulties are thus absent. Representations are not used to engage with prior knowledge, areas of difficulties and new concepts. | The necessary prior knowledge is spoon-fed; thus, strategies to address gaps and difficulties are absent. The teacher seldom facilitates discussions that reveal learners' understanding of concepts. The teacher asks lower order questions that elicit choruses or yes/no answers. The teacher ignores responses that are not in line with the expected answer and eventually provides the correct answer. The teacher provides standardised facts and does not clarify the facts through explanations. Representations are seldom used to engage with learners' prior knowledge, areas of difficulties and new concepts. | The teacher utilises strategies to uncover some learners' prior knowledge and address gaps and/or difficulties in it. The strategies include questions that elicit prior knowledge and representations that support conceptual change. The teacher often asks higher-order questions in some stages of the lesson that allow learners to reveal their understanding and to identify areas of difficulty. Representations are often used to support conceptual change based on learners' difficulties and to support conceptual development for new concepts. | The teacher utilises strategies to uncover all learners' prior knowledge and address gaps and/or difficulties in it. The strategies include questions that elicit prior knowledge and representations that support conceptual change. The teacher asks higher-order questions in various stages of the discussion to allow learners to reveal their understanding and to identify areas of difficulty. Representations are used to engage with prior knowledge, difficult concepts and new content to support conceptual change and development. |

Similar to personal PCK, the enacted PCK rubric was used to assess and quantify the quality of the PCK within the key ideas separately. Furthermore, the information from different sets of observations and interviews was intergrated to obtain a holistic score in the components of PCK. In instances where there were extremities, the scores were aggregated. For example, if a teacher uses two different representations where one representation supports new knowledge while the other promotes a misunderstanding, then the teacher would be scored at the second level.

### 3.9.4 Learners' tests

The performance of the learners was determined from the tests using memoranda that contained the correct answers to each question asked. The scores obtained by the learners in the tests represented their levels of performance in the content that was assessed. However, the evidence of conceptual understanding as reflected by the scores was explored through content analysis. Content analysis is a research method used to examine written or visual data to identify specific characteristics in the data (Ary et al., 2006). In this study, I examined the understanding, or the lack thereof, revealed by the learners in their responses to various types of test questions, e.g. multiple-choice questions.

### 3.9.5 The relationship between PCK and performance

As indicated earlier, this study used a mixed (QUAL/quan) method research approach to investigate the relationship between teachers' PCK and learners' performance (Creswell, 2014). The data reflecting teachers' concept specific PCK was gathered and analysed using qualitative strategies and assigned a quantitative score reflecting its quality. Similarly, the performances of the learners were also averaged according to the key ideas that were chosen for this study. Relationships between learners' performance and teachers' PCK were then investigated for each key idea, separately for the personal and the enacted PCK. Pearson's correlation coefficients were calculated to determine the strengths and the directions of the correlations. Each learner's score was paired with that of their teachers' PCK, creating multiple data points (n = 95 learners for personal PCK and n = 133 for enacted PCK). P values were also calculated accordingly to determine the significance of correlations.

The relationship was also explored using qualitative content analysis, which according to Maree (2010), refers to an iterative and inductive process whereby similarities and differences in the characteristics are used to corroborate or disconfirm a theory. In this study, content analysis was also used to examine any similarities and differences between teachers' explanations and learners' understanding. The focus was on comparing the manner in which teachers explained the aspects of the fundamental concepts against the learners' responses in the test items that explored those aspects.

## 3.10 CHAPTER SUMMARY

This chapter outlined the strategies that were employed to generate and analyse data, including the research principles that guided the adoption of the strategies. As such, it described the paradigmatic perspective, the research approach and the design that guided the study. A pragmatic paradigm necessitated the use of a mixed-method research design as well as a combination of a case study and an ex-post-facto non-experimental design. The sampling strategy was also described, including the participants that were invited to participate. Furthermore, the development and the administration of the instruments used to collect and analyse data that reflected teachers' personal and enacted PCK, as well as the performance of their learners, were described. The next chapter discusses the data that reflected teachers' personal PCK that was collected using the CoRe tool and lesson planning forms.

# 4. CHAPTER FOUR: PERSONAL PCK

## 4.1 INTRODUCTION

This chapter presents the characterisation of the personal PCK of the participating teachers. The data was collected using an adapted CoRe tool and lesson planning forms. As mentioned in the previous chapter, the participating pre-service teachers, Ms VK and Mr JM, each completed the CoRe tool twice and submitted various lessons planning forms. In terms of the in-service teachers, data collection did not proceed as planned. Only one of the two in-service teachers, Ms SH, returned a completed CoRe tool. The other in-service teacher, Mr PM, indicated that he did not have time to complete the CoRe tool, but was willing to participate in the lesson observation, which is discussed in the next chapter. I then proposed an interview to replace the CoRe, but he was reluctant to participate. Regarding lesson planning, both in-service teachers did not provide the plans for the lessons that they presented for this research. Despite these setbacks, I proceeded to collect data that reflect personal PCK from the three cases only. This chapter is thus based on the cases of the two pre-service teachers and one of the in-service teachers, Ms SH.

## 4.2 AN OVERVIEW OF THE ANALYSIS OF PERSONAL PCK

The three case studies are presented separately, with each case discussed in terms of the three supplied key ideas. In short, the fundamental concepts (or key ideas) were as follows: (i) electrostatic force, (ii) electric field and (iii) electric field strength. The teachers' PCK about these key ideas was evaluated using the components of the topic specific PCK model by Mavhunga and Rollnick (2013). The characteristics of each component that I used to assess the PCK of the teachers is summarised in Table 4.1.

*Table 4.1: The major aspects of the components of personal PCK.*

| PCK component | Major aspects of the component |
|---|---|
| Learners' prior knowledge. | • Awareness of concepts that constitute prior knowledge.<br>• Awareness of possible challenges in the prior knowledge. |
| Curricular saliency. | • Indication of new concepts intended for learners.<br>• Indication of the sequential development of the new concepts from learners' prior knowledge.<br>• Indication of the importance of the new concepts, particularly how they shape learners' understanding of other concepts. |
| What is difficult to teach? | • Indication of concepts that are difficult for learners. |

| | |
|---|---|
| Representations. | • Indication of the reasons why the concepts are difficult.<br>• Indication of suitable representations and how they work.<br>• Indication of the concepts that are supported by the representations. |
| Conceptual teaching strategies. | • Indication of strategies used for various purposes drawings from the other components of PCK:<br>- Strategies for teaching main concepts in a key idea.<br>- Uncovering prior knowledge and addressing possible challenges in it.<br>- Uncovering learners' understanding or lack thereof and addressing areas of difficulties. |

In some instances, the teachers gave information that was not relevant to a particular component. However, the information was relevant in reflecting the teachers' knowledge of other components. As such, I analysed the data concerning the components where it was relevant.

## 4.3 CASE STUDY ONE – MS VK

Ms VK participated in this study as a pre-service teacher. As such, the information reflecting her personal PCK was inferred from two CoRe tools and several lesson planning forms. Table 4.2 shows a summary of the PCK scores allocated for each component across the three key ideas. The last row is an overall score per key idea calculated as an average.

*Table 4.2: Ms VK's allocated scores reflecting her personal PCK.*

| **PCK components** | **Electrostatic force** | **Electric field** | **Electric field strength** |
|---|---|---|---|
| Learners' prior knowledge | 2 | 2 | 3 |
| Curricular saliency | 1 | 2 | 2 |
| What is difficult to teach? | 3 | 3 | 3 |
| Representations | 2 | 3 | 3 |
| Conceptual teaching strategies | 2 | 2 | 3 |
| Average | **2** | **2.4** | **2.8** |

### 4.3.1 First key idea: Electrostatic force

***Learners' prior knowledge***

Ms VK's data revealed that she was aware of the concepts that constitute prior knowledge for the electrostatic force. In particular, she referred to the concepts of electrostatics that are taught in Grade 10. The concepts included an atom, the two kinds of charges, the fact that negative and positively charged objects have a surplus and a shortage of electrons respectively as well as the nature of interactions between charged objects. Included in the prior knowledge was Newton's third law and the skills that are applicable when solving problems involving forces. The skills included the ability to add vectors and apply the theorem of Pythagoras when solving 2D problems in mechanics. Because Ms VK interpreted CoRe prompts differently, she listed prior knowledge without indicating learners' possible challenges in it. Furthermore, the lesson planning forms were not designed to explore pre-service teachers' awareness of difficulties in the prior knowledge. Although it is evident that Ms SH was aware of the necessary prior knowledge, there was no information from which her awareness of possible difficulties could have been inferred. Consequently, her competence in terms of prior knowledge was allocated a Level 2 score based on the criteria in the rubric.

***Curricular saliency***

Ms VK's data revealed that she appreciated the importance of prior knowledge and skills as the foundation for the development of new concepts. The prior knowledge and skills included the ability to represent forces using free-body diagrams as well as being able to superimpose forces in a straight line and 2D to find their resultant force. When asked about the importance of the electrostatic force in the curriculum in the CoRe, she responded as follows:

> *Because this will help dealing with charge conservation later after the chapter when the two identical conducting objects having charges on insulating stands touch. Because knowing about the force of interaction between the two charged objects will help them know how to determine the electric field between the charges and with the distance will also help them know how to determine the resultant electric field later…**Because forces of particles produce the electric field and later will work on the electric field and the electric field as a vector**.* (Ms VK)

It is evident that Ms VK's knowledge of the curriculum was restricted in terms of prior knowledge and future concepts. She regarded the electrostatic force as a concept that helps learners understand the conservation of charges. Further evidence emerged from the lesson planning forms when Ms VK included prior concepts under the knowledge that she intended learners to know after the lesson. Similar to the expert CoRe, she appreciated the importance of discussing the electrostatic force before the electric field. However, her reason for this sequence revealed her misunderstanding of the relationship between a force and a field (see bold statement). She implied that electrostatic forces produce electric fields, which is a simplistic view. Based on the rubric, her knowledge of the curricular saliency for the electrostatic force was allocated a Level 1 score mainly based on her indication of the importance of electrostatic forces which was inadequate.

***What makes it difficult to teach this idea?***

Ms VK's data revealed that she was aware of major difficulties associated with learning about the electrostatic force similar to the Expert CoRe (See Figure 4.1).

When substituting into the Coulomb's equation learners tend to include signs and think they give the direction of the electrostatic force, learners must know that sign of the charges they only means the polarity of the charges not the direction.

learners tends to find it difficult to understand why the ~~of~~ same force is exerted on the two ~~charges~~ different in magnitude of the charges

*Figure 4.1: Ms VK's reported difficulties in terms of the electrostatic force.*

She mentioned that learners find it difficult to determine the direction of the electrostatic force. As such, they substitute signs of charges into Coulomb's law and interpret the sign of the final answer as an indication of direction. She also mentioned that learners find it difficult to understand that unequal charges exert the same amount of force on each other, which is a major challenge documented in the literature (e.g. Ajredini et al., 2013; Bohigas & Periago, 2010; Maloney et al., 2001). She also added other difficulties, mentioning that learners do not understand the relationship between force and distance as described by Coulomb's law. In particular, she referred to the learners' inability to calculate the electrostatic force because they forget to convert units and to square the distance between the charges. Despite her clear awareness of the difficulties in this key idea, she did not indicate the causes of the difficulties or gatekeeping concepts. As a result, she was allocated a Level 3 score according to the rubric.

### *Representations including analogies*

Ms VK identified several representations that serve a variety of purposes in this key idea. She indicated that she would explore learners' prior knowledge of charging and charge interactions using balloons, a cloth and a wall. Furthermore, she suggested demonstrating Coulomb's law as follows:

> *Doing the experiment of the fiber and the rod and place the test charge next to the rod shows the electric force between the two charges is proportional to the product of the charges and inversely proportional to the distance between them.* (Ms VK)

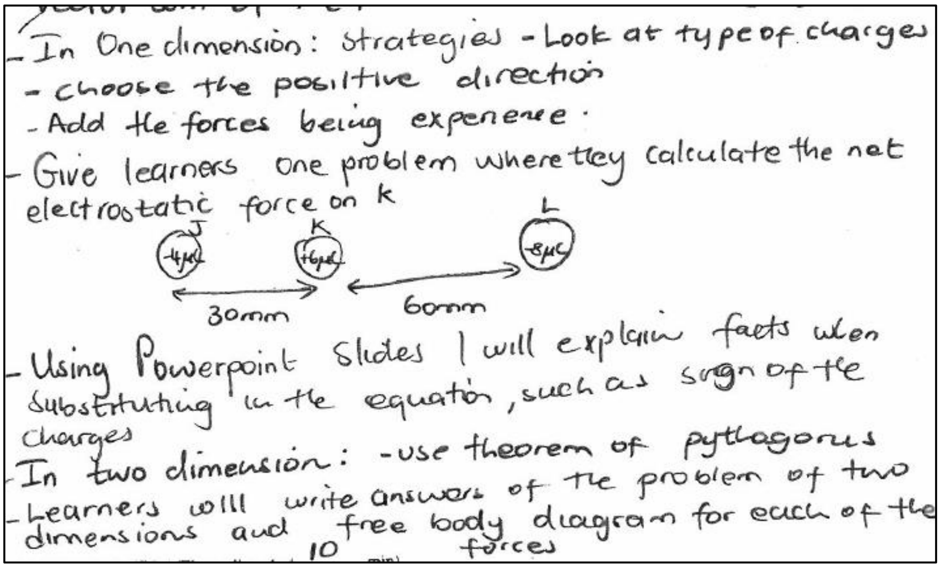
It was not clear to which demonstration she was referring, and there was no explanation of how the demonstration shows Coulomb's law. She also indicated that she would use the following demonstration to support her discussion of the application of Newton's third law: "demonstration of a pencil being pushed to roll and ask learners will the pencil stop. If yes or no why and that could explain Newton's third law." However, she did not explain how this demonstration helps learners understand Newton's third law. The demonstration appears to be better suited for the first and the second law of motion than it is for the third law. When asked about learners' difficulties in the CoRes, she wrote: "sometimes it is difficult as the problem might be more complex in a sense that you have to draw the force body diagrams and their directions". It seems that the complexity she was referring to is the learners' challenges faced when determining the direction of the electrostatic force. This supports her appreciation of the importance of representing forces using vector diagrams in problem-solving, particularly when determining the resultant force on a reference charge. Overall, her discussion of representations was unclear, even though she did refer to vector diagrams and demonstrations. As a result, her competence in terms of representations was scored at Level 2.

### *Conceptual teaching strategies*

In general, Ms VK's teaching strategies was characterised by questions and explanations. Furthermore, the strategies were also shaped by her knowledge of learners' difficulties. Her lesson planning forms indicated that she would start by exploring prior knowledge through questions, for example "what do we mean by neutral objects?” In the lesson planning form, she devised the following strategy for teaching Coulomb’s law:

> *Introduction of Coulomb’s law and his discoveries. Explain the relation of the force and charge together with the square of the distance between charges using slides. Learners will represent the relationship graphically on the whiteboard. From the relationship learners will state Coulomb’s law… I will ask them about the relationship between force and the distance between two charges, like if one increases, what happens to the others.* (Ms VK)

This strategy implies that Ms VK would explain the relationships and request learners to present them graphically and combine them to produce Coulomb’s law. Evidence of a demonstration of Coulomb’s law emerged from the CoRe tool where she indicated that she would use a charged rod and a test charge. However, as indicated earlier, she did not clarify how the demonstration works. Ms VK also devised strategies to address some of the difficulties that she identified. Having indicated that learners find it difficult to understand the application of Newton’s third law, she indicated that she would re-explain the law using a rolling pencil as a demonstration. However, the demonstration seems to be misplaced as it does not indicate force pairs. She also devised the following strategy for solving problems using Coulomb’s law and prior knowledge of mechanics:


- In One dimension: strategies - Look at type of charges
- choose the positive direction
- Add the forces being experience.
- Give learners one problem where they calculate the net electrostatic force on k

- Using Powerpoint Slides I will explain facts when substituting in the equation, such as sign of the charges
- In two dimension: - use theorem of pythagorus
- Learners will write answers of the problem of two dimensions and free body diagram for each of the forces
10 min

*Figure 4.2: Ms VK's reported teaching strategies for the electrostatic force.*

Because learners tend to substitute signs of charges into Coulomb’s law, she indicated that she would instruct them to “look at the type of charges [and] to choose a positive direction”. This implies that she would obtain the directions of the forces from the interactions of the charges and represent them using vector diagrams before superposing them to find their resultant. This is a useful strategy for solving problems involving electrostatic forces. While her knowledge of demonstrations was unclear, she gave a comprehensive explanation of her strategy to teach calculations. According to the rubric, her competence in terms of teaching strategies was scored at Level 2.

### 4.3.2 Second key idea: Electric field

***Learners' prior knowledge***

Ms VK's data revealed that she identified relevant prior knowledge that is necessary for the electric field. The prior knowledge included gravitational and magnetic fields as well as the understanding of the nature of charge interactions and the ability to draw vector diagrams showing electrostatic forces. These prior concepts and skills are important because they relate to the nature of an electric field and they develop the concept of the direction of an electric field obtained using a positive test charge. However, Ms VK did not indicate areas of possible difficulties in the prior knowledge, which, according to the rubric, corresponds with a Level 2 score.

***Curricular saliency***

Ms VK's knowledge of the place of the electric field in the curriculum was evident in the CoRes and the lesson planning forms. She related the electric field with the fields of magnets and gravity by indicating how one field helps learners understand the others. When asked about the importance of understanding an electric field, she wrote the following:

> *[it is important to learn this key idea] because it will help them understand how the magnetic field and the gravitational field works, for example why when throwing the stone up it comes back on earth. It also help them understand why after rubbing the balloon with a cloth, the balloon is attracted to the wall. Representing the electric field around a charged object is important in a sense that it also help on determining if the charge is positive or negative.* (Ms VK)

However, in some instances, she implied that magnetic and gravitational fields are future concepts whereas they actually belong with prior knowledge. Nevertheless, she indicated that she would use the demonstration of a magnetic field using iron filings to help learners visualise fields and their patterns. While in the previous key idea, Ms VK implied that electrostatic forces produce electric fields, she indicated here that an electric field helps learners understand why charged, and polarised objects interact. She also indicated that she would draw electric field lines relative to their source charges and explain that their density is related to the strength of the field. However, she did not link the drawings and the interpretations of field patterns with the next key idea which focuses on the electric field as a physical quantity at a particular point of interest.

The data revealed that Ms VK related different fields, while at times, she seemed to be unsure about their sequence in the curriculum. It was mainly for this reason that her competence was scored at Level 2.

***What makes it difficult to teach this idea?***

The difficulties that Ms VK identified in this key idea were the errors that learners make when drawing electric field patterns. The particular errors in learners' drawings of electric field patterns were as follows; (i) learners forget the directions of electric field lines around a positive and a negative point charge and (ii) they draw electric field patterns incorrectly by having field lines that touch or intersect. The second difficulty is documented in the literature (Taskin & Yavas, 2019; Tornkvist et al., 1993). She also indicated the cause of the errors in the learners' drawings:

> *Electric field [lines] are not real; they are simply tools created by a human being to help people understand how the electric field works, it is difficult to explain something that not real, that learners have to visualise how they look in not something they can see in real life. Field lines exist in three-dimension not only in two dimension as they are drawn and that make it difficult to draw.* (Ms VK)

Indeed electric fields are difficult to conceptualise because they are invisible (Senthilkumar et al., 2014). However, she did not give an example or clarify how the 3D nature of an electric field makes it difficult for learners to draw its patterns. There was evidence of her awareness of the challenges associated with the interpretation of electric field lines. She said, "field lines are drawn closer together where the field is stronger and learners tend to think that are the same throughout." Although she explicitly associated this challenge with the third key idea, it is worth mentioning it in terms of the electric field. Because Ms VK identified difficulties associated with drawing and interpreting field lines while stating the cause of the difficulties, her competence was scored at Level 3.

***Representations including analogies***

Ms VK identified representations that serve various purposes, including uncovering prior knowledge and supporting the development of new concepts. Having indicated that she would relate electric fields with magnetic and gravitational fields, she also mentioned that she would demonstrate a gravitational field by dropping objects.

> *By dropping the pen down from the air, is the representation of gravitational fields…demonstration of throwing an object upwards and explain what causes it to come back to earth…the teacher will throw a stone upwards and ask learners what causes the stone to come back to the thrower's hand or even to the ground.* (Ms VK)

The demonstration of the gravitational field was seemingly going to be aligned with that of an electric field: "presentation on this idea I will use the rubbed ruler with a cloth and use it to pick up pieces of paper, to represent electric fields around a ruler as a demonstration". She also mentioned that she would use iron filings to depict a magnetic field which will help learners visualise a field. Furthermore, she suggested the representation for the discussion of the direction of an electric field:

> *Place the test charge around the charged object to determine whether it is positive charge or negative charge object and would ask what type of force that requires the be determined by test charge through experiment with equipment.* (Ms VK)

The statement is not entirely clear, however, it suggests that she would use a diagram showing a source charge, a positive test charge and note the force on the test charge at different locations around the source charge, i.e. the direction of the electric field. She also mentioned in the lesson planning form that the electric field patterns would be confirmed with a PhET simulation. In this case, the simulation would play a confirmatory role in the direction of the electric field obtained using a positive test charge (Goldberg & Otero, 2003). Given the variety of representations that she mentioned, her knowledge of representations was scored at Level 3.

### *Conceptual teaching strategies*

Ms VK's teaching strategy in this key idea was characterised by the use of representations. As mentioned earlier, she indicated that she would refer learners to their prior knowledge of magnetic and gravitational fields as well as the use of iron filings. Figure 4.3 shows part of her lesson plan about the strategies for teaching the electric field.

8.3 DEVELOPMENT (Time allocated ............min)
*(Continue teacher-learner dialogue to start with new knowledge, learner-centred activities, applicable content, consider questions to guide learners towards critical thinking, show sequence of teaching events, scaffolding, etc.):*

- Ask learners how to determine the electric field around a charged particle? - Positive test charge.
- Define the Electric field and electric field line.
- Explain on how to determine the electric field ~~lines~~ direction on a charged particle.
- Electric field patters around a positive, negative and Between like points and unlike point charges using simulation
- Explain field lines properties using Powerpoint slides.

*Figure 4.3: Ms VK's reported teaching strategies for the electric field, found in a lesson planning form.*

It is evident that she suggested drawing a diagram showing a source charge, a positive test charge and note the force acting on the test charge to explain the direction of the electric field around a point charge. This is a useful strategy recommended in the Expert CoRe. Given her knowledge of difficulties in this key idea, she also devised teaching strategies to address them. Because fields are invisible, she indicated that she would use iron filings to depict magnetic fields to help learners visualise fields. However, she overlooked the fact that the iron filings could address the cause of one of the difficulties that she identified. She mentioned that learners find it difficult to draw electric field lines correctly because the drawings have to be in 2D while the field is actually in 3D. This does not come across as a major challenge. Furthermore, she suggested demonstrating magnetic fields using iron filings on a piece of paper. This demonstration depicts a cross-section of the magnetic field in 2D and would thus address the challenge. Although Ms VK's teaching strategies was dominated by the use of representations, she missed opportunities to use the representations to address known difficulties. As a result, her competence was scored at Level 2.

### 4.3.3 Third key idea: Electric field strength

***Learners' prior knowledge***

Ms VK recognised the electrostatic force and the electric field as the pre-concepts for the electric field strength. She also included vectors and their representations in the prior knowledge for this key idea. Ms VK was aware of possible challenges in the prior knowledge that may hinder successful learning of the electric field (See Figure 4.4).

* Field lines are drawn closer together where the field is stronger and ~~thank~~ learners tend to think that are the same through out
* learners must know that vector has both magnitud and the direction but learners always forget to give the direction of the electric field.

*Figure 4.4: Ms VK's reported prior knowledge for the electric field strength in the CoRe.*

She indicated that learners tend to misinterpret field lines, particularly their density which reflects the strength of the field at a particular region. This is a major challenge that is documented in the literature (e.g. Tornkvist et al., 1993). Tornkvist et al. (1993) reported that learners do not infer the electric field strength from the density of field lines but from individual electric field lines. As such, they think that the electric field remains unchanged along a field line (Saarelainen et al., 2007). I believe that the challenge associated with vectors is minor and could be addressed with ease. Because Ms VK identified a major difficulty associated with the interpretations of field lines, alongside a minor challenge of understanding vectors, her competence was scored at Level 3.

***Curricular saliency***

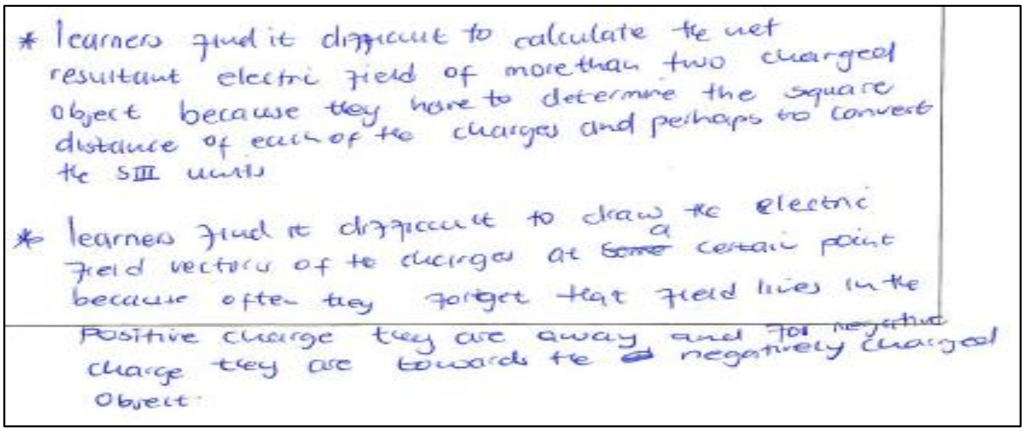
Ms VK's knowledge of the curriculum in this key idea was characterised by her understanding of how the previous key ideas develop learners' understanding of the current one. Some of the links with the prior knowledge were implied while others were explicit. For example, she mentioned that it is important for learners to know the units of measurement of a force and a charge to understand that the electric field strength is measured in Newtons per Coulomb ($N.C^{-1}$). She also said; "using Coulomb's law, I will show them (learners) how to derive electric field equation $E = k\,\frac{Q}{r^2}$". She also indicated in the lesson planning form that the relationships described by the formula $E = k\,\frac{Q}{r^2}$ were going to be represented graphically. However, she did not make it explicit that these discussions would be related with the prior knowledge of electric field patterns, particularly the density of electric field lines as it indicates the electric field strength at a point. Nevertheless, she implied that the electric field lines were going to be used to obtain the direction of the electric field at a particular point when solving problems involving resultant electric fields. When asked about the importance of learning about the electric field strength, she gave a vague response:

> *"Electric field as a vector quantity with magnitude and direction will later help understanding the magnetic field and the electromagnetic fields better and the direction of gravitational fields" (Ms VK). :*

As indicated in the previous key idea, she regarded magnetic and gravitational fields as pre-concepts for the electric field strength, whereas here, she regarded them as future concepts. Nevertheless, she recognised the importance of understanding an electric field as a physical quantity because it leads towards the concept of electromagnetism. As she had a clear understanding of what the curriculum expects, while not having a good idea about the relation of the electric field strength to other concepts, her knowledge in this component was scored at Level 2.

***What makes it difficult to teach this idea?***

Ms VK's reports revealed that she was aware of major difficulties that learners face when learning about the electric field strength. In the CoRe tool, she mentioned that "learners know how to find the magnitude (of the electric field strength) but often forget to write the direction at which the electric field is pointing and that way they always lose marks". She also added other difficulties in the same tool shown in Figure 4.5.


* learners find it difficult to calculate the net resultant electric field of more than two charged object because they have to determine the square distance of each of the charges and perhaps to convert the SI units

* learners find it difficult to draw the electric field vectors of the charges at ~~some~~ a certain point because often they forget that field lines in the positive charge they are away and for negative charge they are towards the negatively charged object.

*Figure 4.5: Ms VK's reported difficulties in terms of the electric field strength.*

Her data reveals that she was aware that learners could calculate the magnitude of the electric field strength. However, they find it difficult to determine the direction of the electric field at a point because they forget the directions of electric field lines around a positive and a negative source charge. As a result, they find it difficult to determine the magnitude and direction of the resultant electric field at a point. She elaborated on the difficulty associated with the resultant electric field at a point as follows:

> *Learners know that when determining the resultant electric fields, the net resultant fields we add, but depending on the direction at which the fields pointing it is not always possible, and learners always find it difficult to solve and loses marks always. Learners have thought of the electric fields between two opposite charges is zero, and when they come to class they find it difficult when the charges are the same. (Ms VK)*

This major challenge has also been reported by Li and Singh (2017). They reported that learners believe that opposite charges cancel each other's field while like charges supplement each other at any point. Given the fact that she reported some of the major difficulties that are documented in the literature and specified the causes of the difficulties, her competence was allocated a Level 3 score.

***Representations including analogies***

Similar to the Expert CoRe, Ms VK suggested using drawings to support her teaching of this key idea. Her selection of this representation was guided by her knowledge of learners' difficulties that she identified. She wrote the following:

> *[I would] present the direction of the electric field at a point using field lines (drawn on the board). Arrows indicate the electric vector to where the fields are pointing, I could use the charts. In a vector representation of an electric field, the length of the vectors indicate the magnitude of the field. (*Ms VK)

Drawings of electric field patterns help learners determine the direction of an electric field at a point. It seems Ms VK suggested drawing electric field patterns and alerting learners to focus on the electric field line that passes through the point of interest as it indicates the electric field at that particular point. However, she did not make it explicit that the representations would be used in this manner, which is suggested in the Expert CoRe. Furthermore, she suggested using vector diagrams showing electric fields at a particular point to support the discussion of the resultant electric field.

Ms VK suggested using suitable representations to obtain the direction of the electric field strength at a point, which addresses the challenge associated with obtaining the direction of the electric field at a point. As a result, her competence was scored at Level 3.

***Conceptual teaching strategies***

Generally, Ms VK indicated strategies for teaching this key idea in a manner that outlined what she would do but not how she would do it. As indicated earlier, she identified an area of difficulty in the prior knowledge that learners do not infer the electric field strength from the density of electric field lines. However, she did not indicate a strategy that she would use to address the area of difficulty before teaching new knowledge. Furthermore, she did not indicate strategies for teaching new concepts, for example the definition of an electric field (*E* = *F/q*) and the derivation of the formula $E = k\frac{Q}{r^2}$. Instead, she only mentioned that she would derive the formula and let learners use it to solve problems on their own. Nevertheless, she indicated strategies tailored for some of the difficulties that she identified. As indicated earlier, she mentioned that learners find it difficult to determine the direction of an electric field at a point because they forget about the directions of electric field lines around point charges. Thus, the teaching strategy that she devised for this challenge is to address the gate keeping concept of electric field lines firstly. Furthermore, she suggested drawing the electric field pattern and implied that she would alert learners to focus on the field line that passes through the point of interest as it indicates the direction of the electric field at that point. This is a useful teaching strategy that is recommended in the Expert CoRe. Ms VK identified other difficulties as indicated earlier. These included learners' inability to determine the resultant electric field at a point caused by a variety of misconceptions. She indicated that learners think that the resultant electric field halfway between equal but opposite charges cancels out, whereas it adds up for unlike charges. However, she did not indicate strategies that she would use to address this difficulty, apart from the drawing of electric field vectors. Despite being aware of some of the major difficulties in understanding the electric field strength, Ms VK only revised a strategy to address the challenge associated with obtaining the direction of the electric field at a point. As a result, her competence was scored at Level 3.

## 4.4 CASE STUDY TWO – MR JM

Mr JM also participated in this study as a pre-service teacher, and as such, his personal PCK was inferred from two CoRe tools and several lesson planning forms that he completed. The scores that were allocated for Mr JM's competence in the components of PCK for each key idea are summarised in Table 4.3. The last row is an overall score per key idea calculated as an average.

*Table 4.3: Mr JM's allocated scores reflecting his personal PCK.*

| PCK components | Electrostatic force | Electric field | Electric field strength |
|---|---|---|---|
| Learners' prior knowledge | 3 | 2 | 2 |
| Curricular saliency | 2 | 2 | 2 |
| What is difficult to teach? | 3 | 2 | 2 |
| Representations | 4 | 2 | 2 |
| Conceptual teaching strategies | 3 | 2 | 1 |
| Average | **3** | **2** | **1.8** |

### 4.4.1 First key idea: Electrostatic force

***Learners' prior knowledge***

Mr JM's data revealed that he was aware of most of the concepts that are needed as the prior knowledge for the electrostatic force. The prior knowledge included the concepts of electrostatics prescribed for Grade 10 in the curriculum as well as the skills that are necessary for solving problems involving forces. Regarding the pre-concepts of electrostatics, Mr JM indicated a major challenge that may hinder successful learning of new knowledge. He said:

> *They (learners) should be able to explain how charged objects can attract uncharged insulators. The difficulty about this pre-concept is understanding that the polarisation of molecules inside the insulator is the reason why charged objects can attract an insulator.* (Mr JM)

It seems Mr JM implied a major difficulty, stating that learners might think the interaction occurs because the insulator is also charged, not understanding the concept of polarisation. He also reported another challenge in the necessary prior knowledge:

> *They (learners) should already know that like charges repel, and opposite charges attract. The difficulty about this pre-concept is understanding that the force causing this is a non-contact force and it depends on the separation distance and size of the charge. For example, if you have $Q_1$ = +1nC and $Q_2$ = -1nC, a learner would expect these charges to attract when separated by 1cm but they fail to understand why they won't at about 100m.* (Mr JM)

This difficulty is inevitable because learners are yet to learn about Coulomb's law. He was acknowledging the fact that learners would know that objects only appear to interact when they are closer to each other without understanding why the interaction is not detectable when they are further apart. Because he identified a major difficulty associated with polarisation, he was allocated a Level 3 score.

***Curricular saliency***

Mr JM reported all the necessary concepts prescribed in the curriculum for learners in this key idea. Some of the concepts were meant to fill the gaps that he mentioned earlier about the relationship between electrostatic force and distance:

> *[After learning this key idea] they will understand better why a piece of paper will be attracted to a ruler that has been rubbed on a cloth or human hair when the ruler is at about 1cm from the paper, and why it won't be attracted at about 30cm from the ruler, i.e. how the distance between two objects affects the force. They will understand that electrostatic is not a contact force like a force one will apply when moving a table. This will help them in understanding the bonding of elements when doing the chemistry part of physical sciences.* (Mr JM)

Mr JM believed that learners struggled with electrostatic forces because they have only been exposed to contact forces in their prior learning. This highlights a gap in his knowledge of the curriculum because the concepts of magnetic and gravitational forces precede the topic of electrostatics in Grade 11 (DoBE, 2011). Nevertheless, he indicated the importance of Coulomb's law, stating that it helps learners understand the bonding of atoms in chemistry. He also recognised the application of the prior knowledge and skills necessary to solve problems involving forces on a straight line and in 2D. These included the drawings of vector diagrams and the theorem of Pythagoras. However, he seemed unclear about the fact that trigonometric ratios also form part of the prior knowledge and skills that learners should already know to obtain the directions of resultant forces in 2D. According to the evaluation criteria, Mr JM was allocated a Level 2 score mainly because he seemed to be unsure that there are other non-contact forces that are scheduled earlier than electrostatic forces in the curriculum.

***What makes it difficult to teach this idea?***

Mr JM identified only one general difficulty in the CoRes about the concept of an electrostatic force and included the cause of the difficulty:

> *The difficult thing about teaching this idea is that the electrostatic force is not a contact force. The reason for this is because, in the previous grades, learners have learned that to move an object you must be in contact with it, so they struggle to accept that there are forces like the electrostatic force that will act on an object even if there is no contact at all.* (Mr JM)

Mr JM did not relate the concept of electrostatic forces with magnetic and gravitational forces which also act over a distance. According to the curriculum, the concept of magnetism and gravitational forces precede the topic of electrostatics. As such, learners would be expected to have an understanding of non-contact forces. Although the lesson planning forms were not designed to explore teachers' awareness of learners' difficulties and their causes, the way Mr JM indicated his teaching strategies revealed his awareness of potential difficulties:

> *In the calculations [of the electrostatic force] I will tell the learners to never substitute the negative signs [into Coulomb's law] because they will be tempted to think that the signs indicate the direction [of the force]… [In cases where $Q_1$ and $Q_3$ exert forces on $Q_2$ simultaneously] I will ask learners the following question; 'which two charges will have a larger force a larger force exerted on each other?' The aim of doing this is to pick up any misconceptions. I know the learners are mostly likely to say $Q_1$ and $Q_2$ will have a larger force because of the separation distance between them, which is not true.* (Mr JM)

Mr JM's awareness of two major challenges was evident in this regard. Firstly, learners substitute signs of charges into Coulomb's law which they confuse with vector characteristics. Secondly, they disregard the influence of the magnitude of charges on the electrostatic force. As such, they think that in a set of two charges exerting forces on a third charge, the closest charge exerts the strongest force regardless of its magnitude. This may have implications when learners have to determine the magnitude and the direction of the resultant force acting on the reference charge.

Seeing that Mr JM revealed awareness of major difficulties, despite not indicating the gatekeeping concepts or causes of the difficulties, his competence was scored at Level 3.

### *Representations including analogies*

Mr JM revealed awareness of several representations that serve a variety of purposes. The representations included the demonstration of a charged ruler and pieces of paper, simulations including the electric hockey game and drawings of vector diagrams. This is how Mr JM reported the use of a charged ruler and pieces of paper to demonstrate Coulomb's law:

> *I will rub a ruler for about a minute on a cloth and use it to pick up a piece of paper…Now to show that between the two objects there is a force and the attraction happens because of it, I will rub the ruler on a cloth again, but now I will place it a bit far from the paper so that it does not attract it, then I will ask why it does not attract the paper…To show that force also depends on the amount of charges, I will rub a ruler for about 2-3 seconds and try to pick up the same piece of paper again from about 1cm above the paper.* (Mr JM)

Similar to the expert CoRe, Mr JM suggested varying the charge on the ruler by rubbing slightly or vigorously, and varying the distance between the ruler and the pieces of paper while learners observe the interactions. The electric hockey game was intended to show learners that it gets very difficult to score a positive puck if more positive charges are placed in goal because this increases the repulsive force. The way Mr JM accounted for the use of vector diagrams was in line with one of the difficulties that he identified. He indicated that he would represent forces using vector diagrams *after* they have been calculated so that the length of the vector corresponds with the magnitude of the force. This representation was meant to show learners that it is not necessarily the closest charge that exerts the strongest force on the reference charge. Following that Mr JM identified suitable representations, including some that were meant to address known difficulties, his competence was scored at Level 4.

***Conceptual teaching strategies***

In general, Mr JM's teaching strategies for this key idea were characterised by questions and explanations. Furthermore, the strategies were shaped by his knowledge of learners' difficulties and representations. In some instances however, he overlooked a representation that could address the area of difficulty that he identified in the learners' prior knowledge. He implied that learners believe that pieces of paper stick to charged objects because they are also charged, not realising that they are in fact polarised. Despite identifying the demonstration of a charged ruler and pieces of paper, he did not mention that it could be used to address this difficulty as the vehicle that drives discussions of polarisation. Nevertheless, he suggested using a charged ruler and pieces of paper to demonstrate and explain Coulomb's law. He also suggested the use of the hockey game to expand the demonstration and explanation of Coulomb's law:

> *[While the learners are playing the electric hockey game] I will ask them why it gets difficult to score the more I add the number of charges. The answer I expect is that the electrostatic force increases when I add more charges, that is, it gets stronger, and the puck is repelled or attracted in a stronger manner.* (Mr JM)

The relationships described by Coulomb's law were also going to be verified through calculations as he indicated in the lesson plan. Mr JM indicated that he would calculate the force before changing the magnitude of the charges or the distance while keeping the other variable unchanged and ask learners to compare the magnitudes of the forces. As indicated earlier, he was aware that learners might substitute signs of charges into Coulomb's law and interpret the sign of the final answer as the direction. His strategy for addressing this challenge was to instruct learners not to substitute signs. However, he did not indicate how the directions of the forces would be determined. Nevertheless, the forces were going to be represented by vector diagrams constructed after their magnitudes have been calculated. This approach was driven by the difficulty that he identified, that is, learners disregard the influence of the magnitude of charges on electrostatic forces. Generally, Mr JM's knowledge of teaching strategies was adequate because he indicated strategies that incorporated representations that supported the discussion of difficult concepts. However, some of the concepts, for example, polarisation and the direction of an electrostatic force, did not have supporting strategies. As such, Mr JM's competence in terms of conceptual teaching strategies was scored at Level 3.

### 4.4.2 Second key idea: Electric field

***Learners' prior knowledge***

The prior knowledge that Mr JM identified for the electric field was limited to the concepts of electrostatics taught in Grade 10. The concepts included the ways of charging through rubbing or contact, the two kinds of charges as well as the nature of the interaction between them. The prior knowledge of magnetic and gravitational fields was not indicated at all in the CoRes as well as the lesson planning forms. Similar to the previous key idea, when asked about learners' difficulties in prior knowledge, Mr JM mentioned challenges that are associated with new knowledge. He said:

> *To be able to do this, learners must already know that there are two types of charges, negative and positive charges. The difficulty comes when they have to represent electric field around two negatively and positively charged objects. They must [also] know that opposite charges attract and like charges repel. The difficult thing learners have about this pre-concept is understanding how the attraction and the repulsion happens. They must know how objects can be charged by contact (or rubbing).* (Mr JM)

It is inevitable that learners would not understand how charged objects interact and how to represent their electric field patterns. Although Mr JM recognised some of the concepts that are prior knowledge for the electric field, he identified difficulties in the new concepts of the electric field and not the prior knowledge. As a result, his awareness of learners' prior knowledge was allocated a Level 2 score.

*Curricular saliency*

As indicated earlier, Mr JM regarded the electrostatic force as the first non-contact force in the curriculum. Similarly, he presented the electric field without referring to the magnetic and gravitational fields that are scheduled earlier in the curriculum. He also suggested a sequence of an electric field and electric field strength that is different from the expert CoRe:

> *I will quickly define electric field (a region of space around in which an electric charge will experience a force). Then I will draw a positive electric charge (+Q) and then tell learners that according to the definition provided above, we have an electric field around that charge and leave the drawing on the board to be used later. Then I will define an electric field at a point (Coulomb force per unit charge) and write the definition mathematically ($E = \frac{F}{q}$). Then I will ask learners to examine this definition and check if whether an electric field is a vector or scalar. The feedback I expect is that an electric field is a vector because the Coulomb force is a vector and the test charge q is a scalar… Then around the region of the positive charge (+Q) drawn at the start, I will draw a positive test charge (+q) and ask learners to predict how the test charge will move if it is brought closer to the positive charge (+Q).* (Mr JM)

Mr JM suggested a thorough discussion of some aspects of the electric field strength before those of an electric field. His suggested sequence was driven by the need to show learners that an electric field is a vector quantity because it is a quotient of a vector and a scalar quantity from $E = F/q$. According to the rest of his lesson planning form, the direction of the electric field would then be explained using a positive test charge. Furthermore, electric field patterns would be drawn after having derived the formula $E = k\frac{Q}{r^2}$ so that the density of field lines around a source charge reflected the relationships described by the formula, hence bigger charges were going to have more fields lines around them compared to smaller ones.

Although Mr JM presented concepts in a sequence that was different from the expert CoRe, his sequence was justified. However, the fact that he overlooked the need to relate electric fields to magnetic fields as recommended in the curriculum leads to his competence being scored at Level 2.

***What makes it difficult to teach this idea?***

Mr JM identified difficulties that were restricted to the errors that learners make when drawing electric field patterns. In particular, he indicated that learners find it difficult to draw electric field patterns showing repulsion (See Figure 4.6). The diagram on the left of Figure 4.6 contains the information that she shared in the CoRe. The diagram on the right was drawn by Mr JM in the lesson plan to illustrate the electric field pattern for two repelling positive charges.

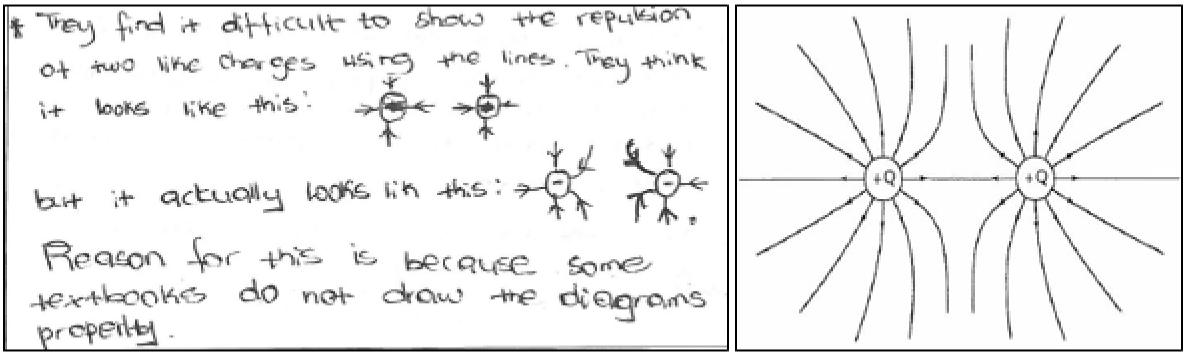



*Figure 4.6: Mr JM's reported difficulties in terms of the electric field in the CoRe and lesson plan.*

As shown in Figure 4.6, he mentioned that learners find it difficult to draw electric field patterns because textbooks present them incorrectly. However, he drew the pattern on the right of Figure 4.7, which contains an electric field line that extends from one positive charge to the other, which is incorrect. Mr JM did not comment on the error in the electric field. This may be an oversight; however, it may have negative implications if it is translated into practice. Some of the difficulties that he reported were challenges faced by teachers:

> *Also, to explain why an object that is more charged will have a greater electric field around it [is difficult]. Reason for this is that some learners and teachers tend to ignore the effect an amount of charge has on an electric field; they are satisfied with the separation distance being the only factor affecting the force.* (Mr JM)

Again Mr JM indicated that the influence of the magnitude of charges is disregarded in the drawings of electric field patterns. It is thus not surprising that he suggested drawing electric field patterns after the formula $E = k\,\frac{Q}{r^2}$ had been derived so that the field lines reflect the relationships described by the formula. He added other causes of the difficulties associated with the drawings of electric field patterns; the fact that electric fields are invisible and three dimensional. Because Mr JM identified difficulties that were restricted to the drawings of field patterns without referring to challenges associated with the interpretations of fields, he was allocated a Level 2 score.

### *Representations including analogies*

It was evident that Mr JM overlooked the fact that the representation of a charged ruler attracting pieces of paper can be used to demonstrate an electric field:

*The difficult thing in teaching this idea [the third key idea] is finding real-life examples that you can use to demonstrate the electric field; one cannot use a ruler and a piece of paper just like in demonstrating the electrostatic force.* (Mr JM)

Nevertheless, he identified a representation that supports the discussion of the direction of field patterns using a drawing of a source charge, a positive test charge and the path taken by the test charge:

*Around the region of the positive charge (+Q) drawn at the start, I will draw a positive test charge (+q) and ask learners to predict how the test charge will move if it is brought closer to the positive charge (+Q). The answer I expect is that the test charge will move away from the positive charge because of repulsion or electrostatic force that the two charges exert on each other. If I do not get the correct answer, I will tell learners to think of Coulomb's law (force). They should be able to say the test charge will move away from the positive electric charge. In this way, we know that around a positive charge the electric field is away from the charge.* (Mr JM)

The rest of the lesson planning form revealed that the same approach would be used to obtain the direction of an electric field around a negative source charge. Mr JM also suggested the use of a simulation to confirm the electric field patterns obtained from using a positive test charge. Furthermore, pictures of snapshots from the simulations were intended to support the discussion of the fact that electric field lines are imaginary, as he indicated in the CoRe. However, there was no indication of how exactly the snapshots would show the imaginary nature of electric field lines.

Mr JM's competence was allocated a Level 2 score mainly because he overlooked the fact that the demonstration of a charged ruler and pieces of paper can support the discussion of electric fields.

***Conceptual teaching strategies***

As indicated earlier, Mr JM identified prior knowledge that included inevitable gaps in the knowledge of the learners. He indicated that learners would not understand how charged objects interacted and they would not be able to represent electric field patterns. However, he also overlooked a representation of a charged ruler and pieces of paper that could be used as a strategy to demonstrate an electric field, the mechanism by which charged objects interact. Mr JM reported two contrasting strategies for electric field patterns in the CoRes and the interviews. His CoRes revealed that he relied on a simulation as it outright displays electric field patterns:

*In teaching them how to draw field lines around two objects that are negatively and positively charged object, I would use a simulation from PhET.com, to show them how the field looks around them and they will have to draw a representation on paper. The simulation does not show* *exactly how the drawing will look like, but it will give them a clue on how the direction of the field will be around each charge.* (Mr JM)

In contrast, his lesson planning form suggested that he would use a drawing of a diagram showing a source and a positive test charge to focus on the discussion of the direction of an electric field (see Figure 4.7).

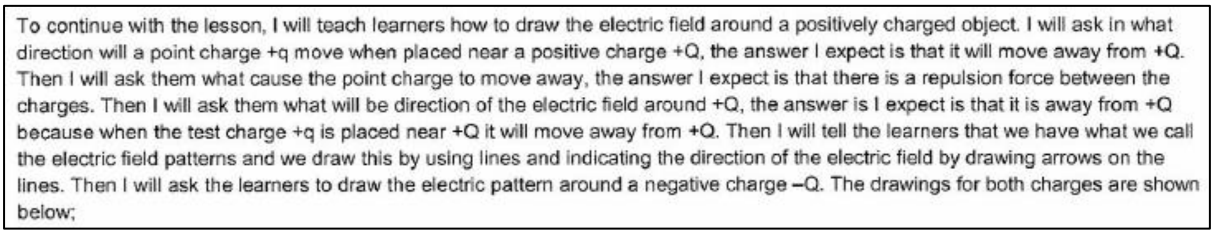

To continue with the lesson, I will teach learners how to draw the electric field around a positively charged object. I will ask in what direction will a point charge +q move when placed near a positive charge +Q, the answer I expect is that it will move away from +Q. Then I will ask them what cause the point charge to move away, the answer I expect is that there is a repulsion force between the charges. Then I will ask them what will be direction of the electric field around +Q, the answer is I expect is that it is away from +Q because when the test charge +q is placed near +Q it will move away from +Q. Then I will tell the learners that we have what we call the electric field patterns and we draw this by using lines and indicating the direction of the electric field by drawing arrows on the lines. Then I will ask the learners to draw the electric pattern around a negative charge –Q. The drawings for both charges are shown below;

*Figure 4.7: Mr JM's reported strategy for obtaining the direction of an electric field.*

The drawings of the electric field patterns were seemingly going to be developed from this discussion rather than the simulation as it was the case in the CoRes. Instead, simulations were going to be used as confirmation of the patterns after they have been drawn based on considering the electrostatic force on a positive test charge at various positions.

The data shows that Mr JM was aware of different approaches for teaching the key idea of an electric field. However, he overlooked the use of the representation of a charged ruler and pieces of papers as a teaching strategy that supports the discussion of the concept of an electric field. As a result, his competence was scored at Level 2.

### 4.4.3 Third key idea: Electric field strength

***Learners' prior knowledge***

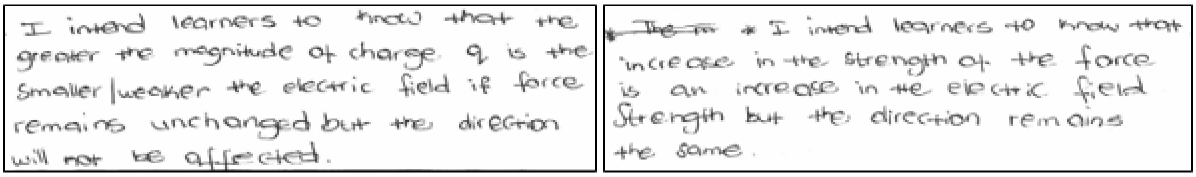
Mr JM acknowledged the first two key ideas as the prior knowledge for the electric field strength. He also included the understanding of vectors and scalars, particularly the ability to add and subtract vectors in the prior knowledge. The only area of difficulty in the prior knowledge that he identified was also associated with vectors and scalars:

> *Learners must already know the difference between a vector and a scalar quantity. The difficult thing they have with this pre-concept is understanding why scalars do not have direction like vectors; that is why a vector is called a physical quantity.* (Mr JM)

I believe that this is a minor challenge that can be addressed with ease. Although Mr JM reported areas of difficulties in the respective preceding key ideas, he did not indicate how they would hinder successful learning of the electric field as a physical quantity. As a result, his awareness of prior knowledge of the electric field strength was allocated a Level 2 score.

***Curricular saliency***

Mr JM's CoRes revealed that he suggested developing some of the new knowledge for this key idea from corresponding pre-concepts. He suggested showing the vector nature of an electric field by scrutinising its definition (*E = F/q*). As such, he deemed it necessary for learners to understand the nature of vectors and scalars as well as their examples. Furthermore, he recognised the importance of Coulomb's law as it is used to derive the formula $E = k\frac{Q}{r^2}$. It was evident that Mr JM's knowledge for teaching the electric field strength was characterised by algorithmic thinking. He mentioned that the importance of learning about this key idea is that "it helps them (learners) in answering multiple-choice questions on electrostatics." Teaching for examination is seen by researchers as a weakness in curricular saliency (e.g. Rollnick et al., 2008). Furthermore, he suggested teaching the electric field strength algebraically by discussing the relationships described by the formula *E = F/q* (See Figure 4.8).



| | |
|---|---|
| I intend learners to know that the greater the magnitude of charge q is the smaller/weaker the electric field if force remains unchanged but the direction will not be affected. | ~~The ...~~ * I intend learners to know that increase in the strength of the force is an increase in the electric field strength but the direction remains the same. |

*Figure 4.8: Mr JM's reported knowledge intended for learners in the concepts of the electric field strength.*

In this regard Mr JM revealed a misconception that has been documented in the literature. He implied that the magnitude of the electric field at a point is determined by the magnitude of the test charge placed at that point (Bohigas & Periago, 2010). According to the evaluation criteria, Mr JM's competence was scored at Level 2 because he emphasised developing algorithms by teaching in a way that prepares learners for examinations.

***What makes it difficult to teach this idea?***

Mr JM identified two areas of difficulties in this key idea of which one was a general challenge while the other was a major problem. The general challenge was that the concept of electric field strength is difficult to teach because of a lack of representations that help learners visualise fields. The second area of difficulty was based on the relationship between the electric field and the electrostatic force on a test charge placed at a point (See Figure 4.9).

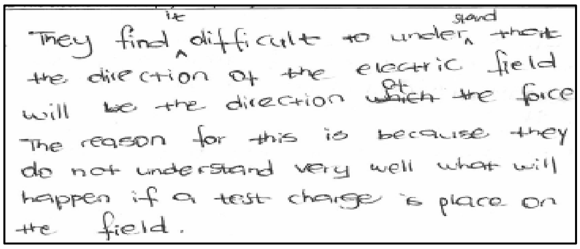

They find it difficult to understand that the direction of the electric field will be the direction ~~which~~ of the force The reason for this is because they do not understand very well what will happen if a test charge is place on the field.

*Figure 4.9: Mr JM's reported difficulty in the electric field strength.*

He mentioned that learners do not understand the fact that the direction of an electric field at a point is the same as that of an electrostatic force (acting on a positive charge placed at that point). He mentioned that this challenge is caused by the fact that learners do not understand the behaviour of charges when they are placed in an electric field. Because only one major challenge was identified, his competence was scored at Level 2.

***Representations including analogies***

Mr JM reported several representations that serve a variety of purposes. These included simulations, pictures and drawings. The simulation and drawings of electric field patterns were meant to show learners that an electric field is a vector quantity because the field lines point in a certain direction. This is additional to what he said earlier about scrutinising the formula *E = F/q* to show learners that an electric field is a vector quantity. He also suggested using pictures that show the direction of the electric field if the force and the test charge are given. This representation was informed by his knowledge of learners' misunderstanding of the direction of the electrostatic force and the electric field at a point. However, he did not indicate what the pictures show and how they reveal the direction of an electric field at that point. Mr JM also suggested using representations to support the discussions of the relationships described by the formulae *E = F/q* and $E = k\,\frac{Q}{r^2}$:

> *To teach this idea (electric field strength) I will most use drawing and the simulation. I will use a drawing showing them point charge q and give them a force at that point; then I will tell the learners to calculate the electric field at that point. Then using their answers, I will ask them what will happen if the magnitude of [test] charge q is increased and decreased; how will that affect the electric field at that point. Using the simulation, I will select different regions that are not at*

*the same distance from the [source] charge, and I will ask them how do the electric fields at these regions compare to one another, and their answers can be verified using the equation* $E = k\frac{Q}{r^2}$ (Mr JM)

The use of representations to contextualise explanations is important. However, in Mr JM's case, the representations were used to support concepts that included incorrect ideas. He indicated that he would use a diagram to explain that changing the magnitude of the test charge results in a change in the electric field at that point because the electric field strength is inversely proportional to the test charge in E = F/q. Although Mr JM identified suitable representations for this key idea, some of them supported the discussion of incorrect concepts. As a result, his competence was scored at Level 2. `

***Conceptual teaching strategies***

As indicated earlier, Mr JM only identified one challenge in the prior knowledge; that is, learners do not know the difference between vectors and scalars. He also did not indicate a strategy to address this challenge before teaching new knowledge. However, he reported a strategy that shows learners that an electric field is a vector:

> *This idea can be best taught by using simulations or drawings. I can use a simulation with two opposite charges that show the electric field. I would ask them why the arrows are pointing at a certain direction. This is done with the hope that they will construct meaning by just looking at the simulation, surely they will come to a conclusion that electric field is a vector since it has direction, then it has magnitude as well.* (Mr JM)

Generally, his teaching strategies for the electric field strength promoted algorithmic thinking and conceptual understanding. For example, as shown in the quote, he suggested using a simulation to show learners the vector nature of an electric field, which promotes conceptual thinking. However, this suggestion is different from the one he wrote in the CoRe tool of using algebraic discussions by scrutinising the formula *E = F/q* to show learners that the electric field strength is a vector quantity. He also suggested a teaching strategy for the discussion of the relationships described by the formula *E = F/q* (See Figure 4.10).

| | |
|---|---|
| I intend learners to know that the direction of the ~~field~~ ~~elec~~ force on the electric field can be determined by placing a positive test charge on the electric field. I intend learners to know that the greater the magnitude of charge q is the smaller/weaker the electric field if force remains unchanged but the direction will not be affected. | To teach this idea I mostly use drawing and the Simulation. I will use a drawing showing them point charge q and given them a force at that point, then I will tell the learners to calculate an electric field at that point. Then using their answer; I will ask them what will happen if the magnitude of charge q is increased and decreased; how will that affect the electric field on that point. Using the |

*Figure 4.10: Mr JM's suggested use of representations for the electric field strength in the CoRe.*

The strategy involves using representations in the form of drawings or simulations. The representations would show the source and the positive test charge as well as various points around the source charge. The representations aim to facilitate discussions, for example asking learners to comment on the electric field at a point if the magnitude of the test charge placed at that point is changed. Although the teaching strategy is reasonable, it again shows his limited understanding of the roles of a source and a test charge. He implied that the magnitude of the electric field at a point is determined by the test charge placed at that point (Bohigas & Periago 2010). Mr JM proposed a similar teaching strategy for the relationships described by the formula $E = k\,\frac{Q}{r^2}$. Furthermore; the formula was going to be used to solve problems involving resultant fields (See Figure 4.11).

| |
|---|
| Now I will teach learners how to calculate the net electric field strength at a point due to two unlike charges and drawing the vector diagram that will help them to in calculating the net electric field strength. The problem that will be used to teach this is phrased as follows;<br><br>Two charges on $Q_1$ = +1nC and $Q_2$ = -2nC are on a straight line, separated by distance 90cm. Point X is located 40cm away from $Q_1$ and 50cm from $Q_2$. Calculate the net electric field strength at point X due to $Q_1$ and $Q_2$. |

*Figure 4.11: Mr JM's teaching strategy for the superposition of electric fields suggested in the lesson plan.*

Mr JM would represent the electric fields using vector diagrams. Thus he deemed it necessary for learners to understand vectors and their additions. However, he did not provide a strategy to obtain the directions of the fields. It seemed as if he did not realise that electric fields exist regardless of anybody measuring them with a test charge. Thus, poor conceptual understanding was reflected in his inadequate conceptual teaching strategies, for which he has been allocated a Level 1 score.

## 4.5 CASE STUDY THREE – MS SH

The data reflecting Ms SH's personal PCK was inferred from a single CoRe tool only because she did not provide any planning documents for the lessons that she presented. The scores that were allocated for Ms SH's competence in the components of PCK for each key idea are summarised in Table 4.4. The last row is an overall score per key idea calculated as an average.

*Table 4.4: Ms SH's allocated scores reflecting her personal PCK.*

| PCK components | Electrostatic force | Electric field | Electric field strength |
|---|---|---|---|
| Learners' prior knowledge | 2 | 2 | 2 |
| Curricular saliency | 2 | 2 | 1 |
| What is difficult to teach? | 2 | 2 | 2 |
| Representations | 2 | 3 | 2 |
| Conceptual teaching strategies | 2 | 2 | 1 |
| | **2** | **2.2** | **1.6** |

### 4.5.1 First key idea: Electrostatic force

***Learners' prior knowledge***

Ms SH's CoRe contained a variety of pre-concepts necessary for the electrostatic force. She presented some of the concepts explicitly as prior knowledge whereas others were implied as such. For example, she suggested relating Coulomb's law with Newton's law of universal gravitation. She also mentioned the application of Newton's third law of motion. The prior knowledge of charge transfer and conservation emerged from one of the questions that she suggested to ask in her teaching strategy. The question read as follows; "two spheres (identical) are allowed to touch, and they immediately push each other away. Explain why this happens". She also identified an area of difficulty in the prior knowledge, stating that "learners have a challenge with the interpretation of inversely and directly proportional." It seems that she was referring to the proportionalities in Newton's law of universal gravitation as it precedes Coulomb's law in the curriculum. Although Ms SH identified some of the prior knowledge, she seldom refers to the potential difficulties in the knowledge. As a result, her competence was scored at Level 2.

### *Curricular saliency*

As indicated earlier, Ms SH related some of the necessary pre-concepts with new knowledge of electrostatic forces. She deemed it necessary for learners to understand the nature and the meaning of proportionalities. When asked about the importance of learning about electrostatic forces, she responded, as shown in Figure 12:

**Question 2: Why is it important for learners to know this idea? Refer to the relation of this idea to other topics in CAPS.**

| 1.1 The force of interaction between two charged objects, and its relation to the magnitudes of, and the distance between the centres of the charges. |
|---|
| - To understand how atoms ~~and~~ are molecules are held together in place. and to be able to measure the forces and their effects before we can use them. Calculate and Solve Problems Involving magnetism. <br> - We can apply Newton's third law to charges because two charges exert forces of equal magnitude on one another in opposite direction. Coulomb's law is similar to Newton's law of Universal Gravitation. $F = \frac{kQ_1Q_2}{r^2}$ and $F = \frac{GM_1M_2}{r^2}$. both laws represent the force exerted by Particles (masses or charges) on each other that Interact by means of a Field |

*Figure 4.12: Ms SH's indication of the importance of the concept of the electrostatic force in the CoRe.*

Ms SH also linked Coulomb's law with Newton's third law as well as the law of universal gravitation. She also appreciated the importance of Coulomb's law because it describes how atoms and molecules stick together in chemistry. Furthermore, she stated that the concept of electrostatic forces helps learners solve problems involving magnetism. However, she did not state the specific concepts of electromagnetism and how electrostatics supports learners in understanding the concepts.

The data shows that Ms SH linked very few concepts of electrostatic forces with prior knowledge and future concepts. Furthermore, the link between electrostatics and magnetism was unclear. As a result, her competence was scored at Level 2.

### *What is difficult to teach?*

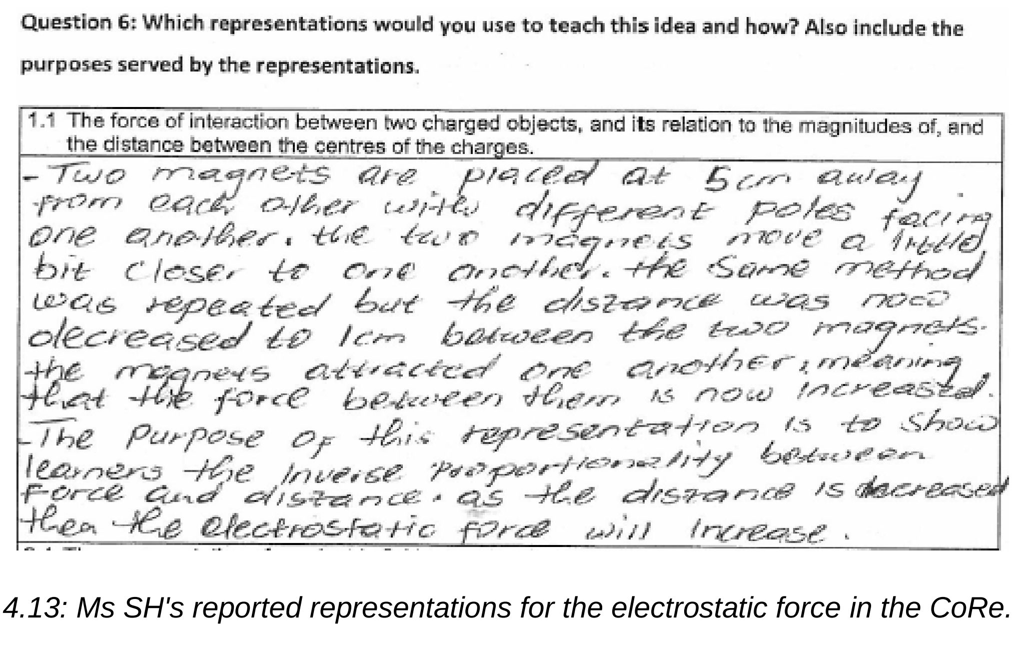
Ms SH only reported one area of difficulty in terms of the electrostatic force. She mentioned that learners find it difficult to understand the inverse square relationship between the electrostatic force between two charges and the distance between them:

*Learners fail to understand the relationship between the force of interaction between two charged objects and the distance between them because of the inverse proportionality. They cannot determine the factor that one component must charge with when changing the other component. They sometimes forget that the distance is squared. Mathematical equations between force and distance is a challenge.* $F \propto \frac{1}{r^2}$ *as the distance is doubled, the force will decrease by a factor of* $\frac{1}{2^2} = \frac{1}{4}$. (Ms SH)

This is a major difficulty that has been reported in the literature (e.g Maloney et al., 2001), which according to Ms SH, is caused by the fact that learners tend to forget the fact that the distance is squared. Furthermore, they do not understand the mathematical implication of squaring the distance on the magnitude of the force. They think that halving the distance doubles the force. This challenge is related to the area of difficulty that she identified in the prior knowledge; that is, learners do not understand the meaning of proportionalities. In this regard, the gatekeeping concept for this challenge was evident. However, because only one challenge was reported, Ms SH's competence was allocated a Level 2 score.

### *Representations including analogies*

Ms SH reported a single representation tailored to support the discussion of the relationships described by Coulomb's law (See Figure 4.13).


**Question 6: Which representations would you use to teach this idea and how? Also include the purposes served by the representations.**

1.1 The force of interaction between two charged objects, and its relation to the magnitudes of, and the distance between the centres of the charges.

- Two magnets are placed at 5cm away from each other with different poles facing one another. the two magnets move a little bit closer to one another. the Same method was repeated but the distance was now decreased to 1cm between the two magnets. the magnets attracted one another, meaning that the force between them is now increased.
- The purpose of this representation is to show learners the inverse proportionality between Force and distance. as the distance is decreased then the electrostatic force will increase.

*Figure 4.13: Ms SH's reported representations for the electrostatic force in the CoRe.*

Ms SH devised an analogy that demonstrates the effect of distance in non-contact forces using magnets. Although the purpose of the analogy is evident, Ms SH overlooked the fact that it may induce a misconception concerning the difference between magnets and charges (Hekkenberg, Lemmer, & Dekkers, 2015).

Nevertheless, because the representation that she suggested does demonstrate the inverse square relationship between distance and non-contact forces, she was allocated a Level 2 score.

***Conceptual teaching strategies***

Ms SH mentioned that she would use a cooperative teaching strategy whereby learners would work in groups. However, she did not specify exactly what the learners will be doing in their respective groups. Her teaching strategy also included explanations of concepts, particularly the relationships described by Coulomb's law as well as the similarities between Coulomb's law and Newton's law of universal gravitation. In this regard, she devised a strategy for addressing the difficulty associated with the inverse square relationship between force and distance. She suggested using two magnets that are placed at various distances to show learners how distance affects their interactions. Ms SH's knowledge of teaching strategies was thus scored at Level 2 mainly because of the use of a representation that demonstrates the effect of distance on non-contact forces.

### 4.5.2 Second key idea: Electric field

***Learners' prior knowledge***

Ms SH CoRe revealed that she regarded the concept of magnetism as prior knowledge for electric field:

> *Learners must know the concept of magnetic field around a bar magnet. They must know the direction of the magnetic field between two magnets placed close to one another with the same or different poles. [They] must know how to draw field lines and the type of the force that the two magnets exert on each other (attraction or repulsion force). [They must also] know the effect of the magnetic force when iron filings were sprinkled on the paper with two magnets placed under the paper.* (Ms SH)

Ms SH revealed a wide range of prior concepts of magnetic fields including their demonstration by iron filings and their representations by field lines. The drawings of magnetic field patterns included the shapes of the patterns that depict attraction and repulsion. However, she did not identify possible areas of difficulty in the pre-concepts of magnetism. Although the prior knowledge of magnetic fields was explicit, that of charge interactions was only implied. She referred to the use of the demonstration of the attraction between a charged balloon and pieces of paper but did not elaborate on how it demonstrates an electric field. As a result, Ms SH's competence was allocated a Level 2 score because she did not mention possible difficulties and/or gaps that learners might have in the prior knowledge.

***Curricular saliency***

Ms SH indicated most of the major concepts prescribed in the curriculum for this key idea. However, the importance of some of the new concepts as well their corresponding prior knowledge was not indicated. It was evident that the prior knowledge of magnetic fields was included mainly because it serves as the foundation to which the drawings of electric field patterns can be developed. This was seemingly based on the fact that the fields of magnets are easily depicted by iron filings. The importance of this key idea was also clearly stipulated, that is, it helps learners understand magnetic fields around a straight current-carrying conductor and a solenoid in the topic of electromagnetism and the concept of Faraday's law. When asked about the concepts that she did not intend learners to know yet (Prompt 3), she wrote the following:

> *The field lines point away from the positive charge and towards the negative charge. It is a radial field, shaped like the spokes of a wheel. We can estimate the force on a test charge that is between two lines by referring to the nearby field lines. Separation of electric charges by means the following methods; by convection in thunderclouds, [and] diffusion of charge occurs in living cells.* (Ms SH)

Some of the concepts that she excluded are important for this key idea. She mentioned that the strength of the field at a point could be estimated by the nearby field line, implying that she was referring to the density of electric field lines as it reflects the strength of the field. This is actually important for learners to know including the direction of electric field lines and the use of the spokes of a wheel as an analogy of a field. Ms SH's competence was thus scored at Level 2 mainly because she regarded some of the key concepts of the electric field as ideas that she did not intend learners to know yet.

***What is difficult to teach?***

Ms SH only identified two areas of difficulties in terms of an electric field. One of the difficulties was accompanied with its cause while the other was not. She wrote the following:

> *There are rules to adhere to when drawing/showing field lines on a charge. Learners sometimes tend to forget those rules and draw the field lines the way they want. Learners also do not understand why the test charge is always positive.* (Ms SH)

Several reports in the literature have shown that learners indeed find it difficult to draw accurate patterns of electric fields (Taskin & Yavas, 2019; Tornkvist et al., 1993). The cause of this difficulty, as Ms SH indicated, is the fact that learners forget the rules that govern the drawings of electric field patterns. The second difficulty that she mentioned is that learners do not understand why the test charge is always positive. However, she did not elaborate on this difficulty. As a result, she was allocated a Level 2 score mainly because she identified two difficulties, even though the second challenge was not clarified.

***Representations including analogies***

Ms SH only identified two representations that support aspects of the electric field. The first representation was the demonstration of the interaction between a charged balloon and pieces of paper. She wrote the following in her CoRe.

> *A balloon was rubbed on a coarse hair so to make it charged, and then cut out some small pieces of paper. Place the side of the balloon that was charged next to the papers. The invisible electric field of the charged balloon attracts the piece of paper. The main purpose of this representation is to show learners the effect of electric field force between two oppositely charged objects.* (Ms SH)

This is a fruitful representation that is recommended in the Expert CoRe for demonstrating an electric field. Although she referred to the invisible field causing the attraction, she then claimed that the balloon and the pieces of paper carried opposite charges, not realising that the papers are actually polarised by the field. The second representation was a drawing of a diagram showing a source charge and the direction of the force acting on a positive test charge to obtain the direction of the electric field (see figure 4.14).

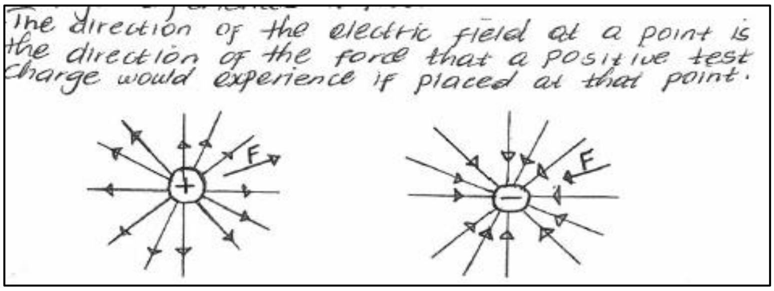



*Figure 4.14: Ms SH's reported representation for the concept of the electric field.*

She was also aware of the fact that the spokes of a bicycle tyre could be used to help learners understand electric field patterns, despite mentioning this information as the knowledge that she did not intend learners to know yet. Nevertheless, her knowledge of suitable representations was adequate following that she identified two demonstrations that are recommended in the CoRe tool. As a result, her competence was scored at Level 3.

***Conceptual teaching strategies***

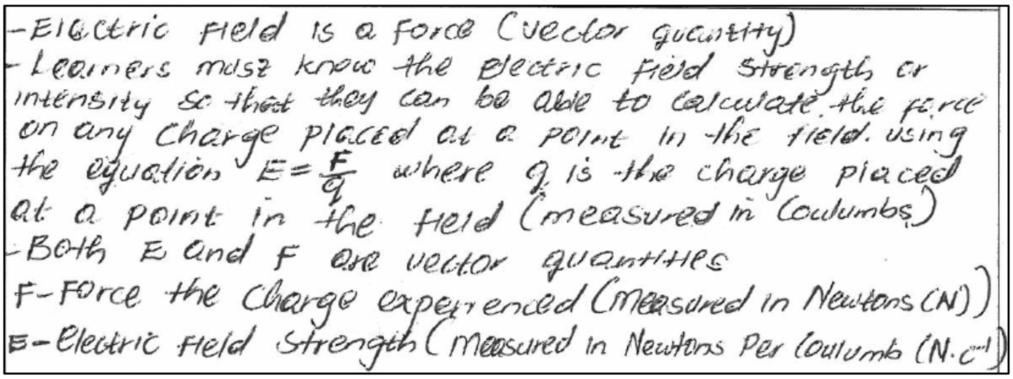
Similar to the previous key idea, Ms SH reported her teaching strategy by listing questions that were summative. One of the questions required learners to indicate the disadvantages of electric field lines drawn on a piece of paper in comparison to the actual electric field. However, she did not specify the disadvantages herself, and thus it was not clear what she meant about the disadvantages of electric field lines that are drawn on paper. Given the fact that Ms SH listed summative questions for this key idea, her knowledge of conceptual teaching strategy had to be inferred from other prompts. As indicated earlier, she identified strategies that support the discussion of the electric field and electric field patterns. She suggested using a charged balloon and pieces of papers to support the description of an electric field; the region of space where a charge experiences an electrostatic force. She also suggested using a drawing showing a source charge and the direction of the force acting on a positive test charge at any point around the source charge. However, she did not make it explicit that she would request learners to study the interactions between the charges to obtain the direction of the force on the test charge, i.e. the direction of the electric field. She also referred to the use of iron filings to help learners visualise field patterns.

Ms SH's data showed that her teaching strategy was dominated by the use of representations. However, there were no explanations of how the demonstrations would be used to facilitate the discussion of concepts. As a result, her competence was scored at Level 2.

### 4.5.3 Third key idea: Electric field strength

***Learners' prior knowledge***

When asked about the necessary prior knowledge for the concepts of the electric field strength, Ms SH responded, as shown in Figure 4.15.



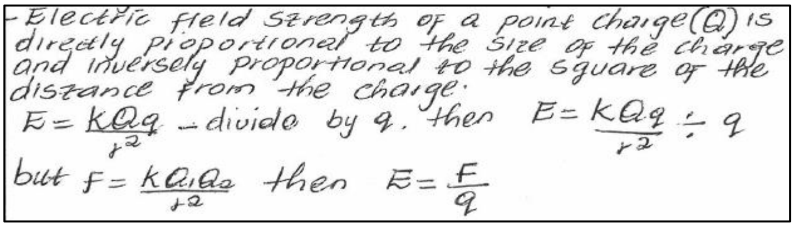
-Electric field is a force (vector quantity)
-Learners must know the electric field strength or intensity so that they can be able to calculate the force on any charge placed at a point in the field. using the equation $E=\frac{F}{q}$ where q is the charge placed at a point in the field (measured in Coulumbs)
-Both E and F are vector quantities
F-Force the charge experienced (Measured in Newtons (N))
E-Electric field strength (Measured in Newtons Per Coulumb ($N.C^{-1}$))

*Figure 4.15: Ms SH's reported prior knowledge for the electric field strength.*

Some of the "prior knowledge" actually included new concepts, for example, the definition of an electric field (*E = F/q*). Nevertheless, Ms SH recognised the importance of a force and a charge as well as their units of measurements and the fact that a force is a vector quantity. However, she did not identify any areas of difficulty in the prior knowledge that may hinder the successful learning of new concepts. As a result, her competence was allocated a Level 2 score.

***Curricular saliency***

Ms SH's CoRe revealed that she was aware of the concepts that are prescribed for the electric field strength in the curriculum. Most of the concepts emerged in the summative questions that she recommended in her teaching strategy. However, one of the questions required learners to determine the magnitude and the direction of the resultant electric field at a point in 2D. This highlights a gap in her knowledge of the curriculum because problems involving electric fields are only limited to a single dimension. Furthermore, she indicated that she would use the formula $E = k\frac{Q}{r^2}$ to derive the definition of an electric field (*E = F/q*) instead of using the definition to derive $E = k\frac{Q}{r^2}$ (See Figure 4.16).



-Electric field strength of a point charge(Q) is directly proportional to the size of the charge and inversely proportional to the square of the distance from the charge.

$E = \frac{kQq}{r^2}$ - divide by q. then $E = \frac{kQq}{r^2} \div q$

but $F = \frac{kQ_1Q_2}{r^2}$ then $E = \frac{F}{q}$

*Figure 4.16: Ms SH's derivation of the formula for electric field strength.*

She implied that the formula $E = k\,\frac{Q}{r^2}$ is a prerequisite for the definition of an electric field not realising that it is actually the other way around. When asked about concepts that she did not intend learners to know yet, she included aspects that are actually important in this key idea. She said, “units of electric field are Newton per Coulomb ($N.C^{-1}$) and volts per metre (V/m) which we still going to learn about when doing electricity.” Although the latter unit of measurement need not be taught at this point, the former is very important and must be discussed with the learners. The majority of the gathered information point out weaknesses in her knowledge of the curriculum. As such, her competence was scored at Level 1.

***What is difficult to teach?***

When asked about learners’ difficulties in this key idea and their causes, Ms SH wrote the following:

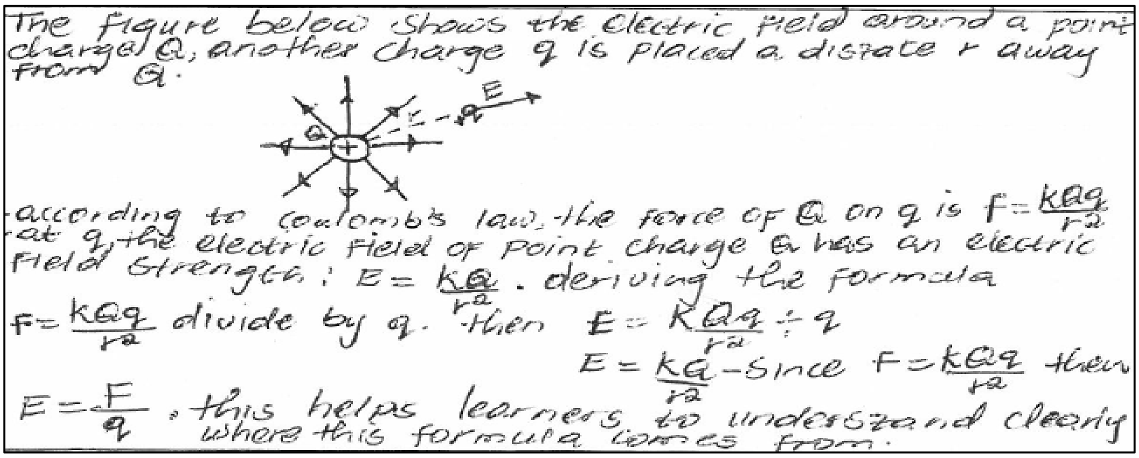
> *Learners fail to understand/know [that] the formula for calculating [the] electric field [is] related to the Coulomb’s law formula, because they have a challenge applying mathematical knowledge or skills in deriving the Coulomb’s law equation. Using and drawing a free body diagram for the net electric field strength that acts on a particular charge [is also a challenge for learners].* (Ms SH)

In this regard, Ms SH identified two areas of difficulty in terms of the electric field strength. She mentioned that learners do not understand the derivation process of the formula for an electric field. It is not clear whether she meant $E = k\,\frac{Q}{r^2}$ or the definition of an electric field ($E = F/q$) because she implied that the former is the prerequisite for the latter. She also identified a generic reason as to why learners have this challenge, indicating that their mathematical knowledge and skills are inadequate. Regarding the second difficulty, Ms SH did not clarify what she meant by the following statement; “free body diagrams for the net electric field strength that acts on a particular charge”. It seems that she was referring to vector diagrams that represent the resultant electric field at a point.

Although Ms SH identified some challenges that learners face in terms of the electric field strength, the causes of some of the challenges were generic and not unique to this key idea. As such, according to the evaluation criteria, her competence was allocated a Level 2 score.

***Representations including analogies***

Ms SH identified two representations that support the discussion of new concepts and problem-solving strategies. She indicated that she would use a diagram showing a source and a positive test charge to support the derivation of formulae (See Figure 4.17).


The figure below shows the electric field around a point charge Q, another charge q is placed a distate r away from Q.

according to coulomb's law, the force of Q on q is $F = \frac{kQq}{r^2}$ at q, the electric field of point charge Q has an electric field strength: $E = \frac{kQ}{r^2}$. deriving the formula $F = \frac{kQq}{r^2}$ divide by q. then $E = \frac{kQq}{r^2} \div q$

$E = \frac{kQ}{r^2}$ - since $F = \frac{kQq}{r^2}$ then $E = \frac{F}{q}$. this helps learners to understand clearly where this formula comes from.

*Figure 4.17: Ms SH's reported representation for the electric field strength in the CoRe.*

The representation is useful in a sense that it contextualises the explanation by showing the locations of the charges, their interactions and how they fit into Coulomb's law. However, as indicated earlier, it seems as if Ms SH was confused about the status of the formulae. She implied that Coulomb's law and the formula $E = k\,\frac{Q}{r^2}$ are used to derive the definition of an electric field ($E = F/q$). Thus although the representation is useful, it was used to support an incorrect concept. The second representation emerged from Ms SH's indication of learners' difficulties. She implied that learners find it difficult to draw and use vector diagrams to represent the resultant electric field acting on a charge. Although the intention to use vector diagrams was not explicit, the fact that she mentioned it indicates that she was aware of its use in this key idea.

According to the evaluation criteria, Ms SH's competence was scored at Level 2 mainly because although she identified useful representations, some of them supported the discussion of incorrect concepts.

***Conceptual teaching strategies***

Similar to the previous key ideas, Ms SH once again listed summative questions under the prompt that explored her knowledge of teaching strategies for the electric field strength. As indicated earlier, one of the questions was beyond the scope of the curriculum as it required learners to determine the magnitude and the direction of the resultant electric field in 2D. Generally, her teaching strategy was flawed by the derivation of the definition of an electric field ($E = F/q$). As indicated earlier, she devised a strategy of using drawings to contextualise the derivation process (see figure 4.17). She also included a useful representation that shows the source and the test charge so that learners understand how they fit into Coulomb's law. However, she did not indicate any questions that she would ask to facilitate the discussions. Furthermore, she implied that the formula $E = k\ \frac{Q}{r^2}$ was a prerequisite for the definition of an electric field, $E = F/q$. In addition, she did not pay attention to learners' mathematical thinking, particularly after recognising it as a gatekeeper towards understanding the derivation process (See figure 4.17). She did not indicate the purpose of dividing the Coulomb's expression by the test charge, q and how she arrived at $E = F/q$. Generally, the derivation process was inadequate from a conceptual and a mathematical point of view. As indicated earlier, Ms SH revealed awareness of learners' inability to draw vector diagrams that help them solve problems. However, she did not report a teaching strategy to address this particular challenge. According to the evaluation criteria, Ms SH's competence was scored at Level 1 mainly because, although she identified some useful strategies accompanied by representations, some of the concepts that they supported were incorrect.

## 4.6 CHAPTER SUMMARY

In this chapter, I presented and analysed data that reflected the personal PCK of three participating teachers; Ms VK, Mr JM and Ms SH. The data was collected using a CoRe tool and a lesson planning form. Because the study focused on PCK at concept level, the CoRe tool was structured in such a way that prompts teachers to present their knowledge about the fundamental concepts of electrostatics namely, electrostatic force, electric field and electric field strength. These fundamental concepts were included in the CoRe as the key ideas that the teachers had to share and on which their knowledge was based. The data was analysed using a rubric that quantified the competence of teachers in each component of PCK on a four-point scale. The scores obtained by the teachers in each component were then averaged to obtain a single score that indicates their overall PCK for each key idea. In the next chapter, I will present and analyse the data that reflected the enacted PCK of the participating teachers.

# 5. CHAPTER FIVE: ENACTED PCK

## 5.1 INTRODUCTION

This chapter presents the PCK that the participating teachers enacted when teaching the topic of electrostatics in Grade 11. Lesson observations were used as the primary data collection strategy that was supplemented by video stimulated recall (VSR) interviews. The interviews allowed teachers to describe their pedagogical reasons that resulted in observable events that unfolded when they carried out classroom instructions. The results are discussed per teacher from Section 5.3 to 5.6.

## 5.2 AN OVERVIEW OF THE ANALYSIS OF THE ENACTED PCK

The enacted PCK of the teachers was analysed using an enacted PCK rubric based on the components of TSPCK in accordance with the key ideas formulated by experts as explained in chapter three. A brief overview of the focus of each of the components of PCK is described in Table 5.1, whereas the full rubric is available in Appendix iii. The rubric was used to quantify teachers' competences in each component of PCK on a four-point scale as follows; limited (1), basic (2), developing (3) and exemplary (4). The competences were then averaged to obtain a single score that represents the overall PCK of the teachers about each key idea.

*Table 5.1: The major aspects of the components of enacted PCK.*

| PCK Component | The major aspects of the component |
|---|---|
| Learners' prior knowledge | • The facilitation of discussions that uncover prior knowledge.<br>• Addressing gaps and difficulties in the prior knowledge. |
| Curricular saliency | • Discussions of concepts prescribed in the curriculum.<br>• Developing and/or linking new knowledge with corresponding prior knowledge.<br>• The sequencing of concepts and the explanation of the interrelatedness between the concepts. |
| What is difficult to teach? | • The facilitation of discussions that uncover learners' understanding of new concepts.<br>• The strategies used to address concepts that are difficult for learners. |
| Representations including analogies | • The use of representations for various purposes; using representations to address difficulties in the prior knowledge, new concepts and to support the development of new concepts. |
| Conceptual teaching strategies | • The use of teaching strategies for various purposes drawing from the preceding components of PCK:<br>• Strategies for uncovering and addressing areas of difficulties in the pre-concepts and new knowledge.<br>• Strategies used when teaching new fundamental concepts. |

For the last of the three key ideas, electric field strength, the teachers did not explicitly refer to prior knowledge. I did not interpret this as poor PCK, because this key idea builds directly on the two previous key ideas of the concept of electrostatic forces and that of an electric field. As a result, the first PCK component was not scored in the enacted PCK for the last key idea. In terms of learners' difficulties across the key ideas, I observed how the participating teachers engaged with the concepts that are regarded as difficult for learners in the literature. These difficult concepts are also listed in the Expert CoRe and Table 5.2 below.

*Table 5.2: Some of the difficulties in the key ideas that are documented in the literature.*

| **Key idea** | **Learners' difficulties** |
|---|---|
| Electrostatic force | • The inverse square law: Learners believe that if the distance between charged objects halves, the force between them doubles.<br>• The application of Newton's third law: Learners think bigger charges exert stronger forces on smaller ones.<br>• Confusion of polarity with vector characteristics: Learners substitute signs of charge into Coulomb's law and incorrectly translate them into an indication of direction. |
| Electric field | • Learners find it difficult to draw accurate patterns of electric fields.<br>• Learners associate an electric field at a point with the test charge placed at that point.<br>• Learners think that electric fields only exist on the actual field lines and not between them.<br>• Learners believe that the electric field is the same along an electric field line instead of being indicated by the density of field lines.<br>• Learners think that all charges placed in an electric field, regardless of polarity move in the direction of the electric field. |
| Electric field strength | • Learners misinterpret the role of the test charge in the definition of an electric field. They believe that the test charge influences the electric field.<br>• Learners confuse the roles of the charges in the formula $E = k\frac{Q}{r^2}$ and $E = \frac{F}{q}$.<br>• Learners substitute signs of charges when calculating the electric field strength. As such, they confuse the polarity of charges with vector characteristics.<br>• Learners believe that the direction of the force and that of the electric field is always the same regardless of the polarity of the charge involved. |

In the discussion of each case study, some of the diagrams that were drawn by the teachers on the board have been recreated exactly as they were for improved visibility. Recreating the diagrams was necessitated by the fact the pictures of the diagrams were unclear when they were captured from the videos.

## 5.3 CASE STUDY ONE – Ms VK

Ms VK participated in this study as a pre-service teacher in an adequately resourced school. Her mentor teacher was seldom present in class while she taught, and as such, she faced challenges with regard to classroom management. A summary of the scores that were allocated for Ms VK's enacted competence in the components of PCK is available in Table 5.3. These scores are then discussed per key idea.

*Table 5.3: Ms VK's allocated scores reflecting her enacted PCK.*

| **TSPCK component** | **Electrostatic force** | **Electric field** | **Electric field strength** |
|---|---|---|---|
| Learners' prior knowledge | 2 | 1 | – |
| Curricular saliency | 2 | 2 | 3 |
| What is difficult to teach? | 2 | 3 | 3 |
| Representations including analogies. | 3 | 3 | 3 |
| Conceptual teaching strategies | 3 | 2 | 3 |
| **Average score** | **2.4** | **2.2** | **3** |

### 5.3.1 First key idea: Electrostatic force

***Learners' prior knowledge***

Ms VK facilitated discussions that explored learners' prior knowledge of electrostatics concepts taught in Grade 10 through questions and explanations. The concepts included polarisation, which she attempted to demonstrate using a ruler and a piece of paper. Unfortunately, the pieces of paper did not stick to the ruler after it was rubbed using hair, a woollen jersey and a jacket. She did not explain as to why the demonstration did not work, and she also did not try to use a different clean plastic ruler. This suggested that she was not sure what the problem was, but the next day she tried to resolve it by asking learners to give reasons why the demonstration did not work. Two learners responded indicating that (i) the ruler and the paper had like charges thus they repelled and that (ii) it must have been the type of the ruler used. This is how Ms VK responded to the learners:

> *Thank you for trying. But then, the problem is his hair was not dry; it was moist. Dry hair attract the static electricity. The dry hair is prone to static electricity, so it attracts the positive electrical charges. During winter the hair gets dry, but it doesn't mean his hair was dry because maybe he uses a moisturiser or something. So it's only the dry hair that can attract the small pieces of the paper. Now let's see if we used a metal ruler instead of a plastic ruler, will the metal ruler pick the pieces of the papers?"* (Ms VK)

Ms VK did not pick up the lack of understanding that was revealed by the first learner. Also, claiming that dry hair "attract static electricity" was misleading. Nevertheless, her response to the second learner was correct in the sense that metallic rulers do not get charged because they are conductors while plastic rulers allow charges to build up in one place. Despite her poor explanations, Ms VK explored learners' understanding of some of the techniques that are used to solve problems involving forces through questions. Based on these observations, she was allocated a Level 2 score in this component.

***Curricular saliency***

It was observed that Ms VK engaged with most concepts and solved a variety of problems on the board in accordance with the curriculum. The link between prior and new knowledge was evident in some concepts, whereas it was missing in others. For example, she used the prior knowledge of charge interactions to obtain the directions of the electrostatic forces acting on the reference charge. The forces were also represented using drawings of vector diagrams, of which some showed force pairs between the charges. Despite showing force pairs, Ms VK seldom discussed the application of Newton's third law in this topic as prescribed in the curriculum. Furthermore, she did not explain the direction of the electrostatic force in 2D due to her insufficient knowledge of the content according to her confession during the VSR interview:

> *Honestly, I didn't know. Even myself I didn't how can I say what the direction is. So I thought let me leave it just before I confuse myself and the learners too. One of the learners did ask "ma'am what is the direction", I said, "no, just go and do it".* (Ms VK)

Although Ms VK sequenced her problem-solving approaches adequately, the connections were inadequate. She indicated the directions of electrostatic forces by describing the interactions between charges, for example, "$F_{L \text{ on } K}$ = 240 N attraction." By not specifying the directions of the forces using cardinal points or left and right, she made it difficult for herself to obtain the direction of the resultant force acting on the reference charge. For example, in one of the problems that she solved, she indicated the direction of the resultant force using the interactions between charges as follows: "$F_{net}$ = 240 N repulsion." Ms VK's was thus allocated a Level 2 score mainly because she did not present knowledge in a way that shows links between the contributing forces and their resultants on a reference charge.

***What is difficult to teach?***

The observations made revealed that Ms VK addressed some of the difficulties that are documented in the literature (See Table 5.2). She did not regard the inverse square law as a difficult concept for learners. At first, she only presented the factors by which forces change when the magnitudes of the charges and/or distance are altered. She only provided explanations when the learners requested her to do so. In one of the discussions, the distance between the charges was halved while their magnitudes remained unchanged. It was observed that Ms VK did not explain how the complex fraction [$F = k\ \frac{Q_1Q_2}{(\frac{1}{2}r)^2}$] transitioned into a simple fraction with a coefficient [$F = 4(k\frac{Q_1Q_2}{r^2})$]. It was also observed that she missed several opportunities to address the difficulty associated with the application of Newton's third law when she drew vector diagrams that showed force pairs. She discussed the application of the law when she had already erased the vectors showing the forces exerted by the reference charge on the surrounding charges. She said:

> *"Another thing guys, your force needs to be the same, like equal. You can't draw the other one like greater than the other one. Remember the Newton's third law? Same force applied but opposite directions."* (Ms VK)

This discussion was misleading, as it suggested that the two forces exerted by two separate charges on the reference charge were equal but opposite according to Newton's third law. It is possible that this may not be what Ms VK meant; however, the presentation suggested otherwise.

Regarding the confusion of polarity with vector characteristics, Ms VK kept emphasising that the negative sign must not be substituted into Coulomb's law. Although she repeatedly provided the reason for excluding the signs, it was misleading. She said:

> *The negative [sign] only indicates that the charge is negative. If you substitute [it in your calculation] your answer is going to be negative. Do we have a negative direction? (Learners responded "No" and she accepted their response).* (Ms VK)

She implied that forces cannot be exerted in a negative direction because such a direction does not exist. Nevertheless, she adequately explained how the direction of the electrostatic force is obtained by referring learners to their prior knowledge of charge interactions.

It is evident that Ms VK seldom addressed difficult concepts, and when she did, her strategies were inadequate. As a result, she was allocated a Level 2 score.

***Representations including analogies***

It was observed that Ms VK used representations to explore learners' prior knowledge and to support the conceptual development of new ideas. Regarding prior knowledge, she attempted to demonstrate charging by rubbing, charge interaction and polarisation through the use of a ruler and pieces of paper. As indicated earlier, the demonstration did not work, and Ms SH did not know how to correct it as she stated in the VSR interview. Nevertheless, she used a drawing of a water molecule and a charged ruler to explain the bending of a weak stream of water when subjected to an electrostatic force. The drawing showed the orientation of a water molecule before and after it interacted with a charged ruler (See Figure 5.1). However, she missed the opportunity to demonstrate the interaction physically using the tap that was in her class.

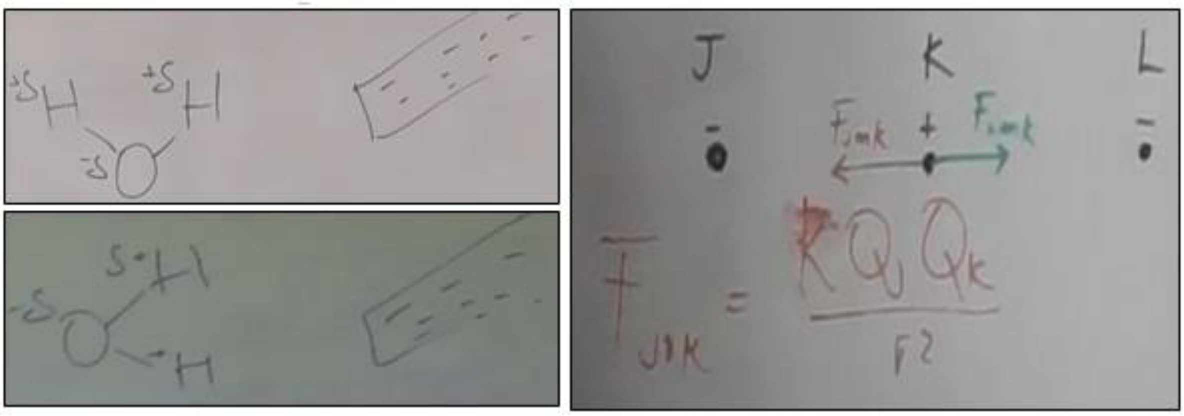



*Figure 5.1: Some of the representations for electrostatic forces used by Ms VK's.*

It was also observed that Ms VK did not use any representations to demonstrate and/or support her discussion of Coulomb's law and only used them when she solved problems. She used the alphabet to label the charges and thus the forces that they exert on each other, for example '$F_{J\ on\ K}$' and '$F_{L\ on\ K}$'. The forces were represented with vector diagrams, with each force vector drawn using a different colour. Similarly, she constructed 2D free body diagrams in a tail-to-tail configuration before changing them into a head-to-tail to show learners that they form right-angled triangles. This was particularly important for showing learners how the theorem of Pythagoras is applicable to such problems. Based on the observations made, Ms VK's competence was allocated a Level 3 score mainly because of the efficient manner in which she used drawings as a part of her problem-solving technique.

***Conceptual teaching strategies***

Ms VK's overall teaching strategy incorporated questions, explanations and the use of representations. For example, she provided an adequate explanation of the phenomenon that was intended by the demonstration of a rubbed ruler and pieces of paper:

> *The ruler initially was neutral neh [right], the moment I bring it close to the piece of papers it doesn't attract because it was neutral. But then as I rub it, it attracts,* ***and it absorbs the paper*** *just because rubbing creates electrical charges.* (Ms VK)

Because Ms VK was not a first language speaker of English, some of her statements, for example that in bold, were misleading. Nevertheless, when explaining the application of Coulomb's law, she facilitated discussions that required learners to apply their prior knowledge of charge interactions, drawings of vector diagrams and the additions of vectors in a straight line and in 2D. She used a book to hide one of the charges to keep learners focused on two charges at a time. She then asked them to study the interactions between the charges and to indicate the direction of the force exerted on the reference charge. Upon getting the directions of the forces from the learners, she represented them using vector diagrams drawn using different colours. She also labelled the forces according to the alphabet that was assigned to the charges in a manner that specified that charge that exerted the force on the reference charge. As indicated earlier, she repeatedly instructed learners not to substitute signs of charges into Coulomb's law. Although she calculated the magnitudes of the individual forces correctly, their connection with their resultant force was inadequate. This follows after Ms VK indicated the directions of the separate forces by describing their interactions. This made it difficult for her to determine the direction of the resultant force in the first problem that she solved (see Figure 5.2).

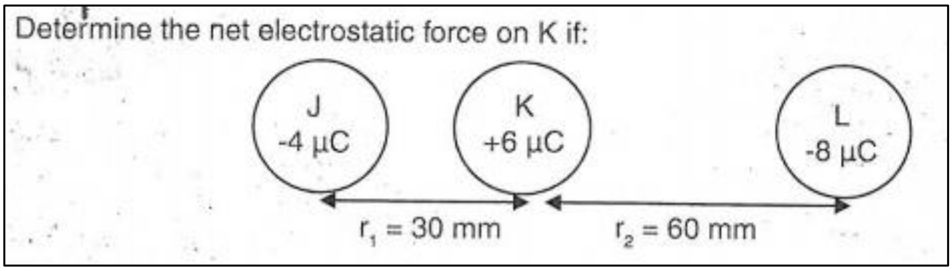



*Figure 5.2: One of the problems of electrostatic forces solved by Ms VK.*

> *Ms VK: The net force will be $F_{J\ on\ K}$ + $F_{L\ on\ K}$, then you add them. But this one [$F_{J\ on\ K}$] is to the left so I expect the answer to be – 240 N plus positive 120 N…then you get your answer [the resultant force], it is going to be 120 N. I know it is negative, but we do not have a negative force right? So the answer (direction of the resultant force) is going to be "repulsion".*
>
> *Learners: "[Repulsion? How is it repulsion?]"*
>
> *Ms VK: "Because it is negative…opposite direction means? Repulsion."*
>
> *Learner A: "Mhm, I don't understand."*
>
> *Ms VK: The direction will be repulsion because this one (while pointing the negative charge) goes to the…like they don't come towards the positi…the negative charge. They go away you see that?. Let's do other examples you will understand.*

This dialogue reveals that Ms VK did not understand that the terms repulsion and attraction are not meaningful to describe the direction of the resultant force. It is also evident that her response was also not well structured and did not refer to the direction of the resultant force, particularly why it is repulsive. During the VSR interview, I asked her to comment on the use of charge interactions to describe the direction of the resultant force, to which she responded as follows:

> *The reason I left 'to the left' 'to the right'…it confused them. Then I stick to the repulsion and attraction. If that one repels with another one, which is positive and positive, and the other one attracts, so it's still going in this direction.* (Ms VK)
>
> *Interviewer: Ok. My question now is; on the net force then? Because if you write repulsion here and attraction here [in the separate forces], what do you write on the net force?*
>
> *Ms VK: That's when I realised that this thing doesn't work like this. If I wrote attraction and repulsion, then the net force will be… Ok if they are both go the same direction, I can't say these two are attracting the particle here [the reference charge].*

Despite the poor explanation of the direction of the resultant, she used good conceptual teaching strategies when solving the rest of the problems. She instructed learners to indicate the directions of the resultant force in a straight line by writing down "left" or "right". Furthermore, she started specifying the directions of the individual forces alongside their charge interactions, for example; $F_{R\ on\ S}$ = 120 N attraction/ left/ negative x-axis. The changed approach enabled her to show links to the individual forces and their resultants in terms of magnitude and direction in a straight line. Considering the fact that she changed her approach upon realising that it was misleading for her and her learners, her competence was scored at level 3.

### 5.3.2 Second key idea: Electric field

***Learners' prior knowledge***

It was evident that Ms VK appreciated the importance of uncovering or presenting the prior knowledge that is necessary for the concept of an electric field. She introduced this key idea as follows:

> *We dealt so many times with charged objects where we had a positive and a negative charge right? A British scientist by the name Michael Faraday developed an idea of an electric field. He said, around a charge object there is electric fields. These electric fields are not real; they are…we imagine them as lines. He said thus electric field can be observed by placing a grain of materials such as a semolina or iron filings. Remember in Grade 10 we used iron filings to observe an electric field…I mean a magnetic field around a magnet bar? That's how he was able to see the electric fields around a charged object.* (Ms VK)

It is recommended in the curriculum that teachers must refer learners to their prior knowledge of magnetic fields, which Ms VK did. However, she revealed a restricted knowledge of the content, stating that electric fields are not real. Furthermore, magnetic fields are not depicted by semolina seeds, and secondly, iron filings do not demonstrate an electric field as she indicated. Her statements suggested that the two fields are the same and are depicted by the same sets of particles, which is a misconception that is documented in the literature (Hekkenberg et al., 2015).

Although Ms VK referred to the prior knowledge of magnetic fields to link them with electric fields, the link was based on incorrect ideas. As such, her competence was scored at Level 1.

***Curricular saliency***

Ms VK discussed all the concepts that are prescribed for this key idea in the curriculum. As indicated in the previous component, she made statements that suggested that an electric and a magnetic field are completely identical. As a result, the distinction between a magnetic and an electric field was not adequately explained. It is evident that Ms VK's knowledge of the curriculum was restricted following that she expected learners to know already what an electric field was and how its direction was obtained, whereas the ideas were actually new:

> *If I have a positive charge like that [while drawing it] and I place a positive charge near this one, it experiences what we call an electric force. The big question is, how do we determine the electric field around this charge? [Silence] Come on anyone? Try guys… [Silence] Okay, to determine the electric field around this charge we use what we call a positive test charge. Is this the first time you hear about this?* (Ms VK)

Nevertheless, she adequately used the prior knowledge of charge interactions to explain the direction of an electric field at a point as the path taken by a positive test charge when it is attracted or repelled by the source charge. Based on the observations made, Ms VK's enacted knowledge of the curriculum was regarded as Level 2, mainly because of the way she obtained the direction of the electric field using a positive test charge.

***What is difficult to teach?***

It was observed that Ms VK presented concepts in a manner that addressed some of the difficulties listed in the Expert CoRe (See Table 5.2). The difficulties were related to the drawings and the interpretation of electric field patterns. Regarding drawings, she emphasised that whenever learners draw electric field patterns, they must make sure that the electric field lines neither cross nor touch. However, she did not provide reasons as to why electric field lines must not touch or cross. Regarding the interpretation of field lines, she explained the relation between the strength of the electric field and the density of electric field lines using two representations (See Figure 5.3). She drew an electric field pattern for a negative source charge and instructed learners to focus on the spreading of the field lines. The electric field pattern was used to explain that the electric field strength weakens with distance as the field lines spread out. She also used a PhET simulation as a confirmation of her explanation by showing learners that the length of the vector on the test charge shortens with distance from the source charge.

*Figure 5.3: Hand drawn and simulated diagrams used by Ms VK when discussing the density of electric field lines.*

The observations revealed that Ms VK addressed some of the challenges pertaining to the drawing and the interpretation of electric field patterns. As a result, her competence was scored at Level 3.

***Representations including analogies***

As indicated earlier, Ms VK introduced this key idea by reminding learners of the demonstration of magnetic field patterns. However, she made misleading statements stating that magnetic and electric field patterns are depicted by either semolina seeds or iron filings. It was thus evident that her knowledge of the demonstrations of electric and magnetic fields was restricted. Nevertheless, she used effective drawings to support the discussion of the direction of an electric field at a point and its pattern around a point charge. She drew a diagram showing a source charge with several positive test charges around it. She also showed the path taken by each positive test charge in its location around the source charge (see Figure 5.4). Ms VK also used PhET simulations to verify the diagrams that she used to obtain the direction of the electric field lines (see Figure 5.4). It was also observed that Ms VK utilised her drawings to develop the concept of electric field patterns for interacting charges. She instructed learners to focus on the paths of the test charges that were placed between the positive and the negative source charge to emphasise the fact that electric field lines point away from a positive charge and towards a negative charge.

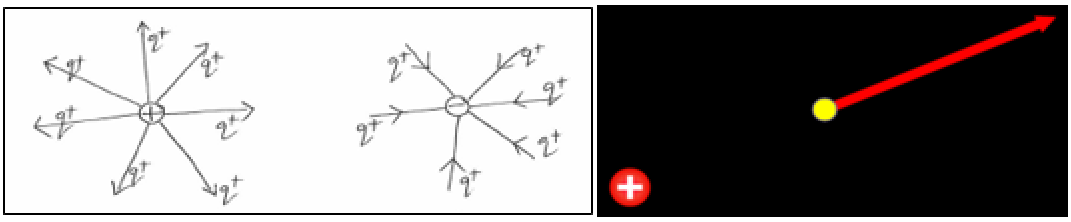


*Figure 5.4: Representations used by Ms VK to explain the direction of an electric field.*

After drawing electric field patterns manually, Ms VK confirmed them using PhET simulation. Although Ms VK made misleading statements about the particles that depict magnetic and electric field patterns, she used powerful graphic representations to develop new knowledge. As a result, her competence was scored at Level 3.

***Conceptual teaching strategies***

Ms VK's general teaching strategies were largely characterised by questions and explanations. Some of the explanations, however, were inadequate as the concepts were incorrect. This was particularly the case in her introduction of the concept of an electric field:

> *A British scientist by the name Michael Faraday developed an idea of an electric field. He said, around a charge object there is electric fields. This electric fields are not real, they are…we imagine them as lines. He said thus electric field can be observed by placing a grain of materials such as a semolina or iron filings. Remember in grade 10 we used iron filings to observe an electric field…I mean a magnetic field around a magnet bar? That's how he was able to see the electric fields around a charged object.* (Ms VK)

She claimed that electric fields are not real and that they are synonymous with magnetic fields. Some of the questions that she used to facilitate learning were also inadequate. She drew a diagram showing a positive source charge to support the discussion of the direction of the electric field.

> *Ms VK: How will the electric field look like if I place a positive test charge there [next to the positive source charge]? [Silence] It is positive, the main charge is also positive. How will the electric field lines look like?*
>
> *Learner A: "Ma'am [madam], I think they [the charges] will move apart."*
>
> *Learner B: "They [the charges] will never touch."*
>
> *Ms VK:" But if you are saying that they are repelling, how do I draw them [field lines]? Here, here, or here [pointing at random points around the source charge]?"*
>
> *Learner B: "The big one with a line going like down and the small one with a line going up."*
>
> *Ms VK: 'We said this one is positive and this one is positive so they repel. So the direction of the electric field will go that way [she drew an arrow showing the force on the positive test charge].*

The question she asked did not instruct learners to focus explicitly on the reference charge. As a result, learner B indicated the directions of the forces that the two charges exerted on each other. In this particular concept, it is the direction of the force acting on the test charge that matters following that it represents the direction of the electric field set up by the source charge at that point. Ms VK then drew other positive test charges next to the source charge to demonstrate the directions of electric field lines at various points around the source charge. This was a good strategy. This strategy was also evident when Ms VK used a PhET simulation to verify the diagrams that she had just drawn by placing the sensor at various points while learners observed the direction and the length of the displayed vector. Based on the observations made, Ms VK's enactment of teaching strategies was scored at Level 2, mainly because her discussions did not guide learners to focus on the positive test charge.

### 5.3.3 Third key idea: Electric field strength

***Curricular saliency***

Ms VK's lessons revealed that she discussed most of the concepts that are prescribed for this key idea in the curriculum. She developed some of the concepts from the corresponding prior knowledge. She defined the electric field as the force per unit charge (*E* = *F/q*) and used it in conjunction with Coulomb's law to derive the formula $E = k\frac{Q}{r^2}$. However, she did not use the definition of the electric field but only used the newly derived formula to solve problems. When she solved problems involving the superposition of the electric field, she utilised the prior knowledge of electric field patterns to obtain the direction of the electric field at the point of interest. She also specified the directions of the separate fields in writing next to their magnitudes, for example: $E_{P, X}$ = 2.13 x $10^4$ $N.C^{-1}$ to the right, using a frame of reference that she chose. The same frame of reference was used to determine the direction of the resultant field. How Ms VK showed links between new concepts and prior knowledge, and the way she used a frame of reference to show the link between separate fields and their resultant was adequate. As a result, her competence was scored at Level 3.

***What makes it difficult to teach this idea?***

It was observed that Ms VK presented concepts in a way that prevented some of the difficulties in terms of the electric field strength that are listed in the Expert CoRe (see Table 5.2). She was cognisant of the fact that learners might think that the test charge affects the magnitude of the electric field of the source charge. She said:

> *To determine the electric field around this [source] charge, we use what we call a positive test charge. Is this the first time you hear about this? [Learners: Yes]. A positive test charge is a very small charge compared to the magnitude of this charge [the source charge]. It is very, very small and is always positive.* ***This test charge does not interrupt the electric field of this charge****.* (Ms VK)

Ms VK was also cautious of the confusion between the role of the source and the test charge. This was observed when she drew a diagram showing a source and a positive test charge which she referred to when she asked learners to indicate the charge that is mentioned in the definition of an electric field (*E* = *F/q*).

> *This force [from $E = \frac{F}{q}$] they are referring to the one where I had the original charge and a positive charge, and I said if I place the second charge near this one it experiences what we call an*

> *electric force. "Per" means the division of this force with the unit of a charge. Now, which charge are they referring to? The main charge?* (Ms VK)

However, she was distracted by the noise made by some of the learners and did not return to her question afterwards. It seems Ms VK had forgotten that she had just asked a very important question. Nevertheless, after deriving the formula $E = k\frac{Q}{r^2}$, she explained its use and that of the definition of the electric field:

> *These are the two equations for electric field [$E = \frac{F}{q}$ and $E = k\frac{Q}{r^2}$]. If you're give a force and a charge, you can be able determine the electric field. If you are only given one charge, and you know this k is Coulomb's constant right, and you are also given the distance you can still find the electric field. D is the distance between this charge [Q] and that small charge [q].* (Ms VK)

The data shows that Ms VK presented concepts in such a way that prevented some of the major difficulties from arising, which, according to the rubric, corresponds with a Level 3 score.

### *Representations including analogies*

It was observed that some of concepts of the electric field strength discussed by Ms VK were supported using representations while others were not. For example, Ms VK derived the formula $E = k\ \frac{Q}{r^2}$ out of context as she did not use a diagram showing a source and a test charge. Nevertheless, she used representations as part of her problem-solving technique. To obtain the directions of the electric fields, she isolated the source charges and drew their electric field patterns. She then instructed learners to focus on the electric field lines that pass through the point of interest as they indicate the direction of the electric field at that point (See Figure 5.5). Upon obtaining the directions of the electric fields, she used vector diagrams to represent each electric field at that point using different colours. She also labelled the vector diagrams adequately to specify the source charges that set up the electric fields at that point, for example, '$E_{Q,X}$'.

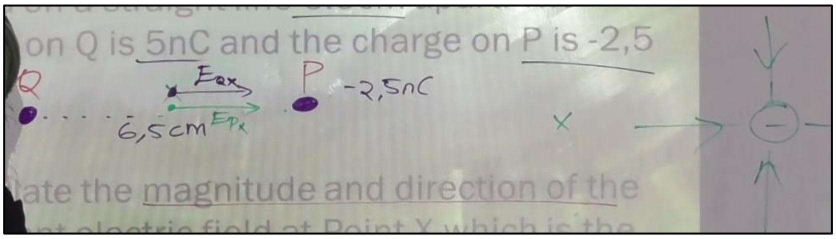



*Figure 5.5: Representations used by Ms VK when teaching the electric field strength.*

The drawings of the vector diagrams were important as they were used alongside a frame of reference to obtain the magnitude and the direction of the resultant electric field at a point. Generally, Ms VK used adequate representations when she determined the magnitude and the direction of the electric field at a point. As a result, she was allocated a Level 3 score.

***Conceptual teaching strategies***

Ms VK's conceptual teaching strategies were mainly characterised by questions, explanations and the use of representations. However, how she derived the formula $E = k\frac{Q}{r^2}$ was inadequate. Firstly, it was derived out of context, and secondly, Ms VK ignored learners' mathematical knowledge of complex fractions. She did not explain how combining Coulomb's law and the definition of an electric field (*E* = *F/q*) produces the expression $E = k\ \frac{Qq/d^2}{q}$. Furthermore, she did not explain how the test charges cancelled out to produce $E = k\frac{Q}{r^2}$. Nevertheless, her conceptual teaching strategies were adequate when she solved problems. She provided three different approaches that are used to determine the direction of the electric field at a point. However, some of the questions that facilitated the discussions of the techniques were inadequate. For example, when explaining the first technique, she asked:

> *We are looking for the direction using this [the point of interest] as the reference. Using this [point] as a positive charge, as a sensor, remember the simulation that I've shown you? This due to this one, the electric field will go to the… ?* (Ms VK)

The first technique was to consider the point of interest as a positive test charge and study its interaction with the other charges. However, the question did not instruct learners to study charge interactions. As such, it was difficult for learners to understand, which prompted Ms VK to provide a different explanation. This time she asked learners to look at the polarity of the source charges, for example, if the charge is positive, then its electric field points away from it. She provided this explanation while she drew vector diagrams showing the electric fields set up by the two source charges (See Figure 5.5). When learners failed to understand the directions yet again, she provided the third technique. This time she isolated the negative charge and drew its electric field pattern and placed point x next to it according to the original diagram. She then instructed learners to focus on the electric field line that passes through the point of interest as it indicates the direction of the electric field at that point. According to the reaction of the learners, the third explanation proved to be useful. It was observed that Ms VK then used a frame of reference to help learners see the link between the individual electric fields and their resultant at a point of interest. Based on the observations made, Ms VK's competence was scored at Level 3 mainly because she kept trying different explanations until she found one that works when solving problems.

### 5.4 CASE STUDY TWO – Mr JM

Mr JM was assigned a mentor teacher who was also the head of the department of physical sciences in the hosting school. The mentor teacher chose to be involved in some of Mr JM's lessons. At times she asked questions to check if learners understood what Mr JM had just explained. She also helped Mr JM understand some of the questions that learners asked and explained some concepts where she felt it necessary. However, her involvement was minimal and was only limited to the first key idea. A summary of the scores allocated for Mr JM's competences in the PCK components in each of the key ideas is available in Table 5.4 below. These scores are then discussed per key idea.

*Table 5.4: Mr JM's allocated scores reflecting his enacted PCK.*

| **TSPCK component** | **Electrostatic force** | **Electric field** | **Electric field strength** |
|---|---|---|---|
| Learners' prior knowledge | 2 | 1 | – |
| Curricular saliency | 2 | 3 | 2 |
| What is difficult to teach? | 3 | 2 | 3 |
| Representations, including analogies. | 3 | 2 | 3 |
| Conceptual teaching strategies | 2 | 2 | 2 |
| **Average score** | **2.4** | **2** | **2.5** |

### 5.4.1 First key idea: Electrostatic force

***Learners' prior knowledge***

Mr JM explored learners' understanding of basic electrostatics concepts taught in Grade 10 by asking questions. The concepts included the two kinds of charges, their associated subatomic particles, the nature of interactions between like and unlike charges as well as the unit of measurement of a charge. He also uncovered and/or presented learners with the necessary prior knowledge needed to solve problems involving three charges on a straight line and in 2D. For example, he explored whether learners remembered that a force is a vector quantity that must it be accompanied by direction. Most of the prior knowledge that was presented for learners was intended for the discussion of 2D problems involving three charges. In the first 2D problems that he solved, he said:

> *If you are looking at this thing [the free body diagram], you can see that they [the forces] are at a 90˚ angle. So it means to be able to calculate the net electrostatic force you need to think of Pythagoras theorem.* (Mr JM)

He guided learners to formulate the theorem in the form of $r^2 = x^2 + y^2$. Furthermore, he explored their understanding of the direction of the resultant force in 2D using a question which learners failed to answer. He then showed them how the direction is obtained by constructing its vector in a tail-to-tail configuration of forces. He then told them that the direction is obtained using trigonometric ratios and presented in the form of an angle. I believe that providing the prior knowledge for learners shows limited insight into the gaps and challenges that they might have in the knowledge. It was also observed that Mr JM did not uncover learners' understanding of Newton's third law from the mechanics' point of view. According to the evaluation criteria, Mr JM's competence was allocated a Level 2 score.

***Curricular saliency***

Mr JM discussed most of the concepts that are prescribed in the curriculum for this key idea. He also showed links between prior knowledge and new concepts at various stages of his lesson. For example, he obtained the directions of the forces acting on the reference charge from the prior knowledge of charge interactions. The forces were also represented with vector diagrams that were drawn in proportion to the magnitudes of the forces. The diagrams were drawn in this manner because of the sequence in which Mr JM solved problems. He did not immediately focus on the reference charge. Instead, he grouped it with the other two charges forming two charge pairs and emphasised that there must be two forces because there are three charges (See Figure 5.6).

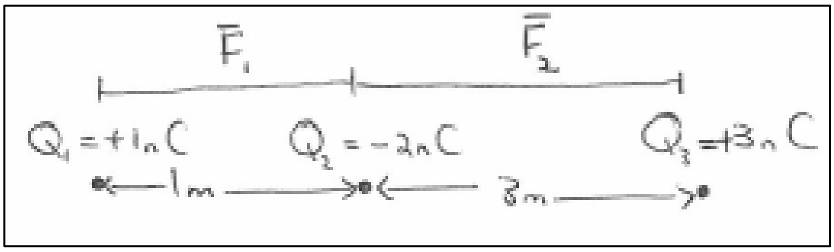



*Figure 5.6: Mr JM's denotation of electrostatic forces.*

Because the focus was not on the reference charge yet, the labels $F_1$ and $F_2$ were used to represent the forces between each pair. As such, the directions of the forces acting on the reference charge were not specified. Instead, Mr JM indicated direction by describing the nature of interactions between the pairs, for example, "$F_1 = 1.8 \times 10^{-8}$ N repulsive." How he presented information provided an opportunity to discuss the application of Newton's third law, which Mr JM missed. He only discussed it once when he was interrupted and instructed during the lesson by his mentor teacher. In addition, while engaging with prior knowledge of charge interactions, he drew a diagram showing vector diagrams extending from two unlike charges to show an attraction. However, the vectors were of unequal lengths. When I asked him to comment on the possibility of inducing a misunderstanding of the application of Newton's third law during the interview, he said: "there I was more concerned about the direction, not the force. I was concerned about where the charge would move." As he proceeded to solved problems, he did not specify the directions of the separate forces acting on the reference charge. He emphasised the importance of specifying the direction of the net force only:

> *And now what is the direction [of the net force]? To the left neh? Because now it is clear. You are talking about one charge there [the reference charge], that's why now you can be able to specify whether it is to the right or to the left instead of attraction here [$F_1$] and attraction here [$F_2$].* (Mr JM)

Based on the gathered data, Mr JM's enacted knowledge of the curricular saliency of this key idea was scored at Level 2. This score was allocated mainly because the connection between the separate forces and their resultants were inadequate due to an absence of a reference frame.

***What is difficult to teach?***

It was observed that Mr JM presented concepts in a manner that prevented some of the difficulties that are documented in the literature (see Table 5.2). He explained how alterations in the magnitudes of the charges and distance affect the magnitude of the electrostatic force. However, he did not discuss the two effects separately. Instead, the magnitudes of each charge was doubled while that of the distance was halved. It was evident that learners struggled to understand the denominator of the following expression $F = k\,\frac{2Q_1 2Q_2}{(\frac{1}{2}r)^2}$ when Mr JM presented it. The learners were uncertain as to why the letter 'r' was included in the expression because they thought it is equal to a half and thus had to be replaced by it. Upon picking up the misunderstanding, Mr JM addressed it as follows:

> *Let's understand the statement. The statement is not saying the distance is equal to a half, they are saying they are halving the distance. If your distance was 'r' before, what is the half of 'r'? It is $\frac{r}{2}$. The statement says r is halved, not r is equal to a half. If this r was four, then r is halved, it means your new r will be four over two, which is the half of four.* (Mr JM)

He also explained the transition from the complex to a simple fraction as well as the coefficient of the expression. Mr JM also explored whether learners consider the relationships described by Coulomb's law when constructing vector diagrams. After drawing a set of three charges on a straight line, he asked learners to indicate the charge that exerts the strongest force on the reference charge. The learners indicated that the closest charge exerts the stronger force, suggesting that they only focused on the relationship between force and distance and disregarded the magnitudes of the charges. As a result, he emphasised that they must pay attention to the magnitudes of the charges and distance because it is not true that the closest charge will always exert a stronger force. This is the reason why Mr JM constructed vector diagrams only after the magnitudes of the forces had been calculated so that the lengths of the vectors corresponded with the magnitudes.

It was observed that Mr JM addressed the difficulty associated with the substitution of the signs of charges into Coulomb's law.

> *So [if you substitute the negative sign] you will be tempted to say…uhm…if you get a negative sign here [a negative force] you will be tempted to say it's going to the left neh. But we are actually calculating the force that the two objects exert on each other. But if you are looking at one charge, then you can say to the left or to the right. But now it's because we are looking at the direction of the force that the two charges exert on each other.* (Mr JM)

Mr JM acknowledged the problem of substituting signs in Coulomb's law, that is, learners would translate polarity into vector characteristics. Furthermore, he adequately explained how to obtain the direction of the electrostatic forces by studying the interaction between charges. How Mr JM explained and addressed most of the concepts that are difficult for learners was adequate. As a result, his competence was scored at Level 3.

***Representations including analogies***

It was observed that Mr JM seldom used representations to engage with learners' prior knowledge. The only time he used representations was when he discussed the application of Newton's third law whereby he physically pushed a desk while mentioning that it pushes back with the same amount of force in the opposite direction. When explaining new knowledge, Mr JM used drawings of diagrams as part of his problem-solving technique. The diagrams showed force pairs as well as the forces that were acting on the reference charge after they had been calculated. The forces were labelled as $F_1$ and $F_2$, and as a result, they did not specify the charge that exerted the force and the one that experienced it (See Figure 5.7). The following discussion took place shortly afterwards:

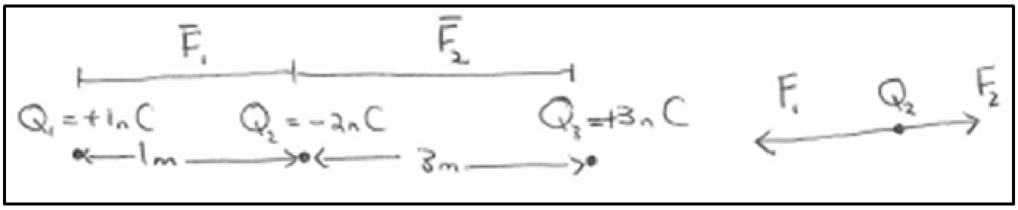



*Figure 5.7: Some of the diagrams used by Mr JM to solve problems involving electrostatic forces.*

> *Learners: "Sir, we are confused. Why don't you write $F_{2\ on\ 1}$?"*
>
> *Mr JM: You must get used to it [to the way he denoted the forces as $F_1$ and $F_2$], when you get to university it is [labelled] like that… Ok, let's say this is $F_1$ and this is $F_2$. It's fine if you do it like this just to show that it is different forces.*

Mr JM missed the opportunity to use a denotation that learners are used to, even after his mentor teacher also recommended it. It was observed that Mr JM incorporated a different representation to help learners conceptualise the effect of a resultant force in a straight line.

> *Another way you can think of it [the resultant force] you have to compare the two vectors neh? This one is larger than that one. So it means this one will make the charge, $Q_2$, to move to the left because it's larger. The two forces if you compare, if I'm pulling something, let's say we are*

> *pulling each other and you are able to come towards me, it means I have a larger force compared to you neh? (He then did a tug of war with one learner) If I'm pulling her and she comes to me, it means I have a larger force neh?* (Mr JM)

When solving 2D problems, he used different labels for the forces. He started with the numbers $F_1$ and $F_2$ before replacing them with the axes of the Cartesian plane to produce $F_x$, $F_y$ and $F_r$. He also changed the configuration from a tail-to-tail to a head-to-tail to show learners how the forces fit into the theorem of Pythagoras.

His use of representations was predominantly adequate, particularly the fact that the forces were constructed relative to their magnitudes and the tug of war demonstration. As a result, his competence was allocated a Level 3 score.

***Conceptual teaching strategies***

Mr JM's overall teaching strategy was characterised mainly by questions, explanations and the use of representations. It was observed that he confirmed the relationships described by Coulomb's law through calculations whereby he changed the magnitudes of the charges and/or the distance while learners calculated the forces on their own. How Mr JM organised and presented information when solving problems was informed by his awareness of a potential difficulty for learners. He acknowledged one of the difficulties by asking learners to indicate the charge that exerts the strongest force on the reference charge in a set of three charges on a straight line. When responding to the question, learners mentioned that it was the closest charge, implying that they disregarded the effect of the magnitudes of charges in the electrostatic force while they focused on distance only. This is how he addressed the difficulty:

> *So you don't consider the charges now, you only consider the distance? [There was no response]. If you are going to look at distance, we must have ama charges lawa ukuthi abe the same, angithi? [The charges must be the same, right?]. So if this was 2, 2, 2 [if all the charges were 2nC], the obviously this [the closest charge] was going to be the larger one like you are saying.*

This was the reason why he only constructed vector diagrams after the forces acting on the reference charge had been calculated.

It was observed that Mr JM instructed learners not substitute signs of charges in their calculations because they might translate them into vector characteristics. Furthermore, he used questions to prompt learners to study the interactions between charges to they can be able to determine the directions of the separate forces acting on the reference charge. However, some of his questions were misleading as they were not properly phrased, as shown in the following example when Mr JM added separate forces to obtain their resultant in a straight line.

> *Mr JM: To be able to know which one will be negative, you look at the force there which one is the larger one. The larger force will have the negative sign. [Waited a bit before asking] What did I just say about the two forces, how would I know which one will be negative and which one will be positive?*
>
> *Learner A: "If the force is to the left, it means it is negative, and if it is to the right, it means it is positive."*
>
> *Mr JM: "That's wrong, what you're saying is not what I just said. You have to compare the two forces, you can see that $F_1$ is larger than $F_2$, therefore $F_1$ will have a negative sign."*
>
> *Learner B: "Ok, what if the larger one is to the right?"*
>
> *Learner C:" But Sir, you said we should look at the magnitude of the forces… [Mr JM interrupted]"*
>
> *Mr JM: We said two things, you can look at the magnitude and the direction as well. If you are looking at the magnitude, it doesn't matter I can still make this one [the force to the right] a negative. You will still get the same answer, but it will be positive here [the net force]. So whatever you are comfortable with, looking at the direction or you look at the size of the vectors. But the direction is best to look at it because you are used to direction from Grade 10. You know that if it goes to the right, it is positive, and if it goes to the left it is negative.*

Although this dialogue tapped into the prior understanding of vectors, it was confusing because it is not necessarily the stronger force that takes the negative sign, but the force exerted in the chosen negative direction. It appeared that Mr JM was trying to convince learners that even if they had chosen a different reference frame, they would still obtain the same magnitude and direction of the resultant force. When asked about this interaction in the interview, he acknowledged the potential misunderstanding that may have been induced. He said:

> *The way I said it is a bit… [misleading] I was concerned if they can interpret the vector diagram that I have drawn there. I should have been specific for this case only. I was referring to this specific diagram. It's sort of a universal thing that's how they choose it. Looking at that diagram, the answer I expected is that the longer one will get a negative. When I think about it now…I should have been specific that it's for this case only.* (Mr JM)

Mr JM also solved 2D problems using the same approach that he utilised when problems involving charges in a straight line. That is, he did not label forces adequately to show the charges that exerted the forces on the reference charge. Furthermore, the directions of the forces were not specified, instead, charge interactions were used to describe the directions. Based on the observations made, he was allocated a Level 2 score in terms of conceptual teaching strategies.

### 5.4.2 Second key idea: Electric field

***Learners' prior knowledge***

It was observed that Mr JM did not explore learners' prior knowledge of magnetic fields to relate them with electric fields as recommended in the curriculum. Nevertheless, he revealed his appreciation of learners' prior knowledge of charge interactions which he used to explain the direction of an electric field at a point using a positive test charge. However, because Mr JM disregarded the prior knowledge of magnetic fields, he missed an opportunity to uncover learners' general understanding of a field and its representation. As a result, his competence was scored at Level 1.

***Curricular saliency***

Mr JM discussed most of the concepts that are prescribed in the curriculum for this key idea. However, he did not relate the concept of an electric field with magnetic fields as indicated earlier which is recommended in the curriculum. It was observed that Mr JM explained some aspects of the third key idea before engaging with this key idea. In a nutshell, he described and then defined the electric field as the force per unit charge. Before discussing electric field lines, he used the definition of an electric field [$E = F/q$] in conjunction with Coulomb's law to derive the formula $E = k\,\frac{Q}{r^2}$. When asked in the interview about deviating from the curricular sequence, he said:

> *I wanted to get them…uhm…to get them to start thinking of an electric field strength before we can start drawing and doing everything. So when we start drawing, let's say it's a charge at this point, Q. The reason I started bringing that first, I was thinking of…when I start asking questions if I'm here at point x and here at point y, I wanted them to answer having the effect of distance in mind. So I wanted to bring that one in before I can go straight to drawings, the directions and everything. When I was busy with drawings, the way I planned it, I planned that when I get to drawings, there will be a point where I ask that when I'm standing there, and I'm standing here, what's the difference, which one is the strongest electric field. Looking at the drawings only without performing calculations. The idea of bringing that in was to emphasise how distance affects the electric field.* (Mr JM)

This sequence was driven by the need to draw electric field patterns in such a way that reflects the relationships described by the formula $E = k\,\frac{Q}{r^2}$. Thus, bigger charges were surrounded by many field lines in comparison to smaller ones. However, he did not explain that electric field lines spread out with distance from the source charge as the strength weakens. Nevertheless, he adequately used the prior knowledge of charge interactions to explain the direction of an electric field as the path taken by a positive test charge when it is attracted or repelled by a source charge.

Mr JM's knowledge of curricular saliency was scored at Level 3 because of the justification of the sequence he followed as well as how he explained the direction of the electric field.

***What is difficult to teach?***

It was observed that Mr JM presented concepts in a way that prevents some but encourages other difficulties that are listed in the Expert CoRe (see Table 5.2). He instructed learners to ensure that they draw electric field lines that neither touch nor cross, as shown in the conversation:

> *Mr JM: You should not have something like this one [the drawing of crossing field lines] and have the lines crossing each other. It is very wrong. They cannot cross each other or touch each other because if you have something like this one, then at this point [the intersection] there's no longer a repulsion. Even if it is unlike charges, they shouldn't cross each other.*
>
> *Learner A: "But they should touch?"*
>
> *Mr JM: "Yes they can touch each other in the middle. They don't actually touch each other, it is just one line."*

The conversation also shows that he explained why electric field lines must not touch. However, when explaining the direction of an electric field using a test charge, he made a statement that could encourage a misunderstanding that the direction of the electric field at a point and that of the electrostatic force acting on a charge at that point is always the same (Bohigas & Periago, 2010).

> *Learners A: "Sir, is the test charge always positive?"*
>
> *Mr JM: Ja [yes] that's why I'm using…[He paused for a while] It can be a negative one, but it's better to understand it with a positive one. Just stick to a positive one. If you use a negative one it means you must change the whole idea again and come with different explanations.*

During the VSR interview, he actually defended the use of a negative charge as a test charge stating that learners should not be limited to one method of determining the direction of an electric field. Looking at the difficulties that he addressed, and the manner in which he addressed them, particularly the use of a "negative" test charge, Mr JM's competence was scored at Level 2.

***Representations including analogies***

After having explained briefly that an electric field is a vector and how its magnitude is calculated, Mr JM moved on to explain how its direction is determined using drawings. He drew a positive charge, +Q, and placed a positive test charge, +q next to it (See

Figure 5.8). When learners indicated the path taken by the test charge as a result of the force exerted on it by the source charge, Mr JM represented it with an arrow. He then used the diagrams to emphasise the fact that the direction of the electric field is away from a positive charge and towards a negative charge.

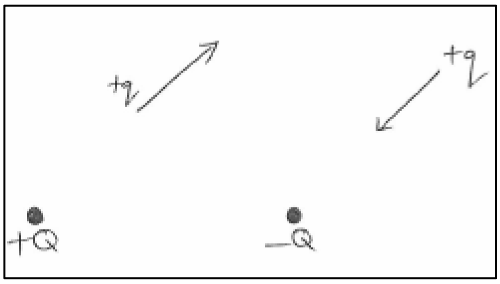



*Figure 5.8: Representations used by Mr JM when discussing the direction of the electric field.*

The drawings of electric field patterns were developed from these diagrams; that is, electric field lines point away from a positive and towards a negative charge. Given the fact that Mr JM used one type of representation, drawings, his competence was scored at Level 2.

***Conceptual teaching strategies***

Mr JM's general conceptual teaching strategies were characterised by questions and explanations. Some of the explanations were misleading, for example, when he mentioned that a test charge could be negative. In actual fact, he defended this explanation during the VSR interview when I asked him about it:

> *Mr JM: In my mind, I can still be able to know the direction of the electric field even if I'm using a negative test charge. I will still go back to the attraction and repulsion because if I'm putting a positive [source] charge and I'm bringing a negative test charge you expect the test charge to move in that direction [towards the source charge] because it is attracted by that one, they are unlike charges.*
>
> *Interviewer: "So the direction of the field here, how will you then explain it to the learners?"*
>
> *Mr JM: "Mhmm that's a bit [complicated]…ja I see because based on this one it is supposed to be out. The direction of the electric will be in the opposite direction in which this charge will move.*
>
> *Interviewer: "If you were to teach this again and a learner asks you 'is it always positive?'. Would you answer it the same way and say it can also be negative, but you just reverse the direction?"*
>
> *Mr JM: I would answer the same way because when I teach, I don't want to teach learners to stick to one thing of determining something. They should have different ways of doing this. So that was the idea that they could be more than one way of doing something.*

Using a negative test charge could make learners think that all charges, regardless of polarity move in the direction of an electric field, which is a misconception documented in the literature (e.g. Bilal & Erol, 2009). Nevertheless, he formulated good questions that required learners to study the interactions between a source and a positive test charge when he explained the direction of an electric field at a point (refer to Figure 5.8):

*Mr JM: "If I'm bringing the [positive test] charge closer to this positive charge here [+Q], what will happen when they get closer to each other?"*

*Learners: "They will repel."*

*Mr JM: "Meaning that the [positive test] charge will move to what direction?"*

*Learners: Away.*

*Mr JM: "The direction in which this charge moves when you place it there, that's the direction of the electric field. If this charge moves away, it means the electric field around this charge is away."*

Mr JM then emphasised that the source charge is stationary while it is the positive test charge that moves in the direction of the electric field. Thus based on how he explained the direction of an electric field at a point, his competence was scored at Level 2.

### 5.4.3 Third key idea: Electric field strength

***Curricular saliency***

As indicated in the previous key idea, Mr JM briefly discussed aspects of the electric field strength before engaging with the general overview of an electric field. It later became evident that Mr JM followed this sequence because he wanted to firstly show learners that an electric field is a vector quantity. He defined the electric field ($E = F/q$) and used the definition to deduce the vector nature of an electric field since it is a quotient of a vector and a scalar quantity. He also derived the formula $E = k\frac{Q}{r^2}$ and used it to solve problems in a systematic sequence, starting with electric fields set up by isolated charges before discussing the superposition of electric fields. However, Mr JM did not deem it necessary to specify the directions of separate fields in writing and to decide on a specific frame of reference. After having calculated the magnitudes of the separate electric fields, he gave an inadequate response to one of the learners:

*Learner A: "Sir, so direction for $E_1$ is repulsion or away?"*

*Mr JM: "At this point when you are doing the calculations don't worry too much about indicating the direction."*

*Learners: "Why not, Sir?"*

> *Mr JM: "Don't worry about it, they won't penalise you for now. I will tell you when to worry."*

By not specifying the direction, Mr JM made it difficult for learners to make connections between the separate electric fields and their resultants. As a result, his competence was scored at Level 2.

***What is difficult to teach?***

It was observed that Mr JM presented concepts in a manner that prevented one of the difficulties that are listed in the Expert CoRe from arising (see Table 5.2). The difficulty is that learners associate the magnitude of the electric field at a point with the test charge placed at that point (Bohigas & Periago, 2010). After deriving the formula $E = k\frac{Q}{r^2}$, he explained the fact that the test charge placed at a point in an electric field does not affect the magnitude of the field at that point:

> *The electric field does not depend on this one [pointing on the test charge in the formula E = F/q]. The size of this charge won't affect the magnitude or the strength of the electric field and any point because we use this equation [the one he just derived]. Does this equation have a q [test charge]? [Learners: No] So this means the electric field at any point is independent of the test charge.* (Mr JM)

When I asked him to indicate why he emphasised the fact that the positive test charge does not affect the electric field at any point during the VSR interview, he revealed awareness of another difficulty, responding as follows:

> *My idea was, you know when you have a drawing like this (a drawing showing a source charge and a positive test charge), and maybe in the test, you are given the same drawing. When they ask them to calculate the electric field of the bigger charge. When they start thinking sometimes they make mistakes when calculating it. Instead of using the value of this one [source charge], the use the value of the small one when they get to this equation [$E = k\ \frac{Q}{r^2}$]…My idea was that they should just ignore that (the test charge).* (Mr JM)

However, Mr JM did not uncover and address the difficulty during his lessons. Nevertheless, the fact that he was aware of this difficulty and the manner in which he prevented one of the challenges listed in the Expert CoRe resulted in his competence being scored at Level 3.

***Representations including analogies***

Mr JM used the same type of representation (drawings) to support his discussion of various concepts of the electric field strength. He drew a diagram showing a test charge and a positive test charge to contextualise the derivation of the formula $E =$

$k\frac{Q}{r^2}$ by combining Coulomb's law with the definition of an electric field (See Figure 5.8). He also used a drawing of electric field patterns to help learners understand how the direction of the electric field at a point is determined. However, the drawing was not adequately utilised. Mr JM extended one of the electric field lines going to the left while emphasising that the direction of the electric field remains the same along the straight line. Perhaps he could have extended the line to the right to clarify that the electric field of $Q_1$ at point x was to the right. Furthermore, the field lines on the left of the source charge are touching (See Figure 5.9).

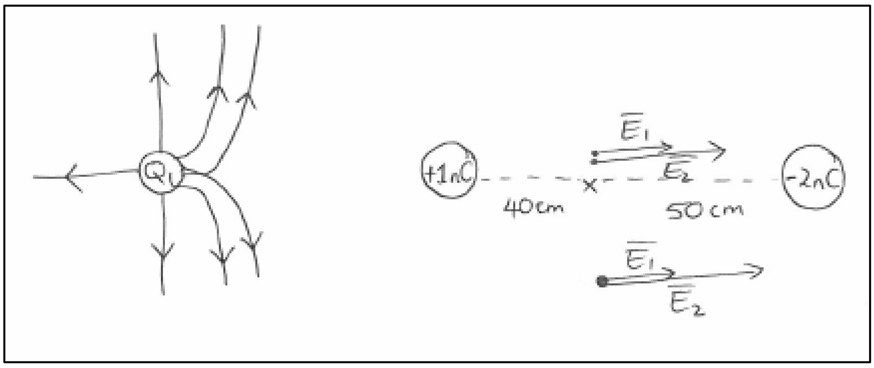



*Figure 5.9: Some of the representations used by Mr JM when discussing the electric field strength.*

Upon establishing the directions of the electric fields at the point of interest, Mr JM represented the electric fields using vector diagrams. The vectors were initially equal in length, suggesting that Mr JM was interested in the direction rather than the magnitudes. After having calculated the magnitudes of the separate fields, he reconstructed the vectors relative to their magnitudes before determining their resultants. How he used representations to support the discussion of most of the concepts was adequate. As a result, his competence was scored at Level 3.

***Conceptual teaching strategies***

Mr JM's conceptual teaching strategies were characterised mainly by questions, explanations and the use of representations. As indicated earlier, he used a suitable drawing to contextualise the derivation of the formula $E = k\frac{Q}{r^2}$. However, he ignored learners' mathematical thinking. His derivation procedure was as follows: $E = \frac{F}{q} = k\frac{Qq}{qr^2} = k\frac{Q}{r^2}$. He did not explain how "q" ended up in the denominator coupled with "r$^2$" despite mentioning that he replaced F with Coulomb's law. When I asked him if he would derive it the same way next time he teaches this idea again, he responded: "I think I'd approach it the same way. The reason I'm doing it like that I expect a question from the learner just like you asked; how did it get to this point?" When solving problems, he used questions to facilitate discussions that required learners to apply their prior knowledge of electric field patterns, as shown in Figure 5.9 and the discussion below:

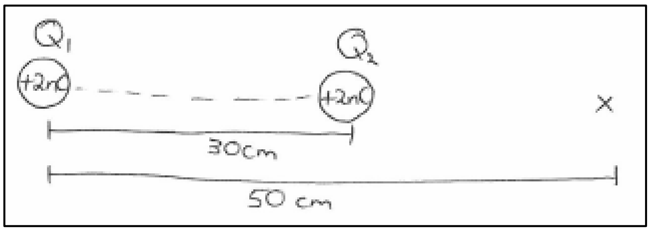



*Figure 5.10: A diagram showing one of the problems involving field superposition that Mr JM solved.*

> *Mr JM:" If you look at that charge $Q_1$, at this point [point x], is the electric field going to point that way or that way [pointing to the left and to the right]?"*

Some learners said to the right, which Mr JM accepted as correct. When some learners asked why the electric field is to the right, he directed the question to other learners.

> *Learner A: "Sir because $Q_1$ is positive and they will repel, because the test charge is also positive."*
>
> *Mr JM: You are correct by saying because $Q_1$ is positive, but don't talk about this one [$Q_2$] [the learner tried to defend his case but was overpowered by the raised tone of the teacher], IGNORE THIS ONE [$Q_2$] so you can't talk of repulsion and everything. Remember, according to what we've been doing here [electric field patterns], if you are drawing an electric field around a positive charge, it will be pointing away. If $Q_1$ was negative, it was going to be towards (while drawing a vector to the left) but because it is positive, it is pointing away.*
>
> *Learners: "Sir, I don't understand."*
>
> *Mr JM: You are looking at $Q_1$. You want to indicate the direction of the electric field around a positive charge. Is it towards or away from the charge? [Learners: away]. Now you are drawing a vector instead of drawing this [electric field pattern].*

Learner A answered based on the idea that underpins the directions of electric fields; the direction of the force acting on a positive test charge. It is evident that the learner imagined a positive test charge placed at point x and studied its interaction with the source charges to establish the directions of the fields at that point. Seemingly, Mr JM misunderstood the learner, thinking that the learner was referring to $Q_2$. Had he allowed the learner to defend his case, he may have picked up that the learner was actually correct. It was also observed that Mr JM isolated one of the source charges and drew its electric field pattern. The aim of using the electric field pattern was to encourage learners to focus on a particular field line at a time, preferably the one that passes through the point of interest as it indicates the direction of the electric field at that point. However, his conceptual teaching strategy was affected by the fact that he did not specify the directions of the individual electric fields and that he did not use a frame of reference to show the connection between the fields and their resultant. As a result, his competence was scored at Level 2.

## 5.5 CASE STUDY THREE – Ms SH

Ms SH's involvement in this study began two days after she had already started teaching the topic of electrostatics. She was invited to participate in the study following the withdrawal of one of the participants that had previously consented to participate in the study. As such, I did not observe how she introduced Coulomb's law, but I managed to observe how she solved problems involving three charges on a straight line and in 2D using the law. Ms SH's classroom was equipped with a smartboard that contained electronic textbooks. The scores allocated for her competence in the components of PCK for each key idea are summarised in Table 5.5. These scores are then discussed per key idea.

*Table 5.5: Ms SH's allocated scores reflecting his enacted PCK.*

| **TSPCK component** | **Electrostatic force** | **Electric field** | **Electric field strength** |
|---|---|---|---|
| Learners' prior knowledge | 2 | 1 | – |
| Curricular saliency | 3 | 1 | 1 |
| What is difficult to teach? | 2 | 2 | 2 |
| Representations including analogies. | 2 | 1 | 1 |
| Conceptual teaching strategies | 2 | 1 | 1 |
| **Average score** | **2.2** | **1.2** | **1.25** |

### 5.5.1 First key idea: Electrostatic force

***Learners' prior knowledge***

As indicated earlier, the observation of Ms SH's lessons began when she was already halfway through the concept of an electrostatic force. As such, I invited her to an interview to explore the aspects of her lessons that I have missed. One of the questions was about her introduction of electrostatic forces and the prior knowledge that has to be in place before teaching about such forces. She responded as follows:

> *The introduction comes from Grade 10, **in Grade 10 they deal with charges, a positive and a negative charge around a magnet**. Ke ba file [I gave them] a baseline assessment first based on Grade 10 work so that they know what is a charge, how do we draw electric fields around a positive charge and around a negative charge and the combination of the two charges. I also looked at that one that says like charges repel and unlike charges attract before we can introduce Coulomb's law.* (Ms SH)

Some of the prior knowledge that she reported was relevant; however, it was limited to the concepts of charges. Furthermore, it included incorrect concepts as shown by the bold statement, suggesting that she had a misconception about charges and magnets that is documented in the literature (e.g. Hekkenberg et al., 2015). Further evidence of this misconception will be provided in the next key idea. Because Ms SH was not observed engaging with the concept of charges, it cannot be concluded that she transferred her own misconception to her learners (Mazibe et al., 2020). Based on the observations, it was evident that Ms SH utilised some of the necessary prior knowledge of charge interactions, vector additions, the theorem of pythagoras and trigonometry when solving problems. The exception was Newton's third law. Although Ms SH did not uncover learners' understanding of these prior concepts, it is possible that she may have uncovered them in the lessons that I missed. Based on the data collected, Ms SH's competence was scored at Level 2 because she engaged with the necessary prior knowledge which she used to solve problems.

### *Curricular saliency*

When I visited Ms SH for my first observation, I found that she was already solving problems involving three charges on a straight line and in 2D. From that point onwards, observed that whenever she engaged with some concepts that develop from, or that are related to prior knowledge, she referred learners to the knowledge. The link between prior knowledge and new concepts was also pronounced in the VSR interview when she said:

> *Normally, I relate Coulomb's law with the law of universal gravitation because their formulas are almost the same. It's just that on the other side they deal with the product of the masses, in Coulomb's law they deal with the product of the charges. The story behind it is the same. So normally, I start with getting them to recall newton's law of universal law of gravitation. Then coming into coulomb's law, they must tell me the difference (between the laws)*. (Ms SH)

She also determined the directions of the forces acting on the reference charge from the prior knowledge of charge interactions. The forces were represented with force diagrams, of which some showed force pairs between charges. Despite showing the force pairs, she did not refer learners to their prior knowledge of Newton's third law of motion. It is possible that the law may have been incorporated into the lessons that I missed. When solving 2D problems, Ms SH referred learners to their prior knowledge of the parallelogram method, the theorem of Pythagoras, and trigonometry.

The sequence in which she solved problems was adequate. She specified the directions of the separate forces acting on the reference charge, for example, $F_{Q1 \text{ on } Q2} = 5 \times 10^{-5}$ N to the left. She also presented a frame of reference, taking the right-hand side and upwards as positive, which she used to obtain the magnitude and the direction of the resultant force. As such, there was an obvious connection between the separate forces and their resultants because the directions were specified from the beginning. Thus Ms SH was allocated a Level 3 score mainly because of the links that she showed between prior knowledge and new concepts, as well as how she sequenced her problem solving approaches.

***What is difficult to teach?***

During the VSR interview, I asked Ms SH to indicate how she introduced and explained Coulomb's law. This question aimed to explore whether she explained the relationships described by the law mathematically using symbols only. For example, the fact that halving the distance between charges increases the force between them by a factor of four. When answering the question, she only referred to the fact that the force is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. Nevertheless, I observed that Ms SH's learners were comfortable with the exclusions of signs, implying that she must have explained that the signs should be excluded. This is how she accounted for the exclusion of signs during the interview:

> *It's because these signs just tell us the direction of the force. If a charge is +5 and another charge is -5, it simply means gore [that] the positive charge, the force will go into [towards] the negative charge. So they just tell us about the direction of the force but they are not included in the calculations.* (Ms SH)

Despite not mentioning the danger of substituting signs, she indicated that the signs reveal the nature of the interactions between the charges. During the lesson, she explained how to determine the directions of the electrostatic forces acting on the reference charge through studying the interactions of the charges. When solving 2D problems, some learners failed to understand the directions of the forces in the free-body diagram that she drew. To address this difficulty, she redrew the diagram, this time showing force pairs between the reference charge and the surrounding charges (see Figure 5.11). This was an opportunity for Ms SH to discuss the application of Newton's third law and address the misconception that unequal charges exert unequal forces on each other. However, she missed it. Based on the information obtained from the interview, the observations and the manner in which Ms SH engaged with difficult concepts, her competence was scored at Level 2.

***Representations including analogies***

Given how Ms SH participated in this study, I was unable to observe whether she used representations to engage with prior knowledge and to demonstrate Coulomb's law or not. Nevertheless, I could observe how she used representations to solve problems in the application of Coulomb's law. Ms SH drew inconsistent free-body diagrams showing the forces acting on the reference charge. In one of the diagrams, there were two separate dots representing the reference charge, whereas in the other, both forces were constructed in the same dot (See Figure 5.11).

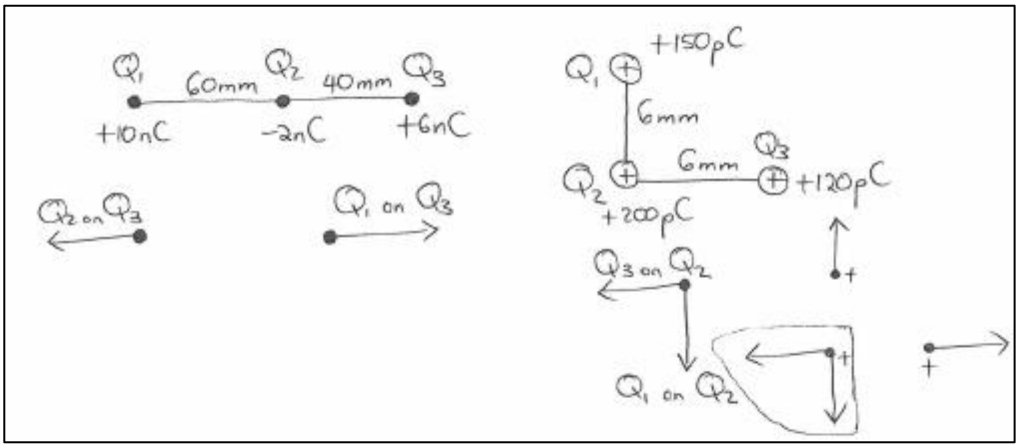



*Figure 5.11: Some of the diagrams used by Ms SH when teaching electrostatic forces between three charges in a straight line (left) and 2D (right).*

When asked about the use of two separate diagrams for the same charge during the interview, she said:

> *Because if you use $Q_2$ as a point charge, and then you draw both then you will have a problem sometimes because these learners need to know that now you're dealing with only two charges,*

> *so the direction of the force must be between the two charges, so as to calculate the force for two charges and the other force for two charges and then at the end, that's when you get the net force. If you draw them on the same charge, some might not get it.* (Ms SH)

It is evident that Ms SH attempted to make use of two separate "free body" diagrams, mentioning that they make it explicit that the two forces are exerted by separate charges. However, the diagram does not show that the two forces are exerted on the same charge, $Q_3$. Nevertheless, the diagrams were labelled adequately, showing the charge that exerted the force on the reference charge, for example $F_{Q1 \text{ on } Q2}$. Regarding 2D problems, she changed the configuration of the free body diagram from a tail-to-tail to a head-to-tail and placed the letters x, y and r on the corresponding sides of the resulting right-angled triangle. This was meant to show learners how the forces fit into the theorem of Pythagoras. She also placed symbol θ, which she used to obtain the direction of the resultant force.

Based on the observations made, Ms SH's use of representations was scored at Level 2. This score was allocated mainly because she used two separate diagrams to represent forces acting on the same reference charge in one of the problems that she solved.

***Conceptual teaching strategies***

Although Ms SH was not observed when introducing Coulomb's law, she was observed applying it to solved problems involving three charges in a straight line and in 2D. In general, the strategies that she used to solve problems were largely characterised by questions, explanations and the use of representations. Furthermore, Ms SH integrated various concepts and skills to support her problem-solving technique. For example, Ms SH facilitated discussions that required learners to study charge interactions to obtain the directions of the individual forces exerted on the reference charge, as shown in the conversation below (refer to Figure 5.12):

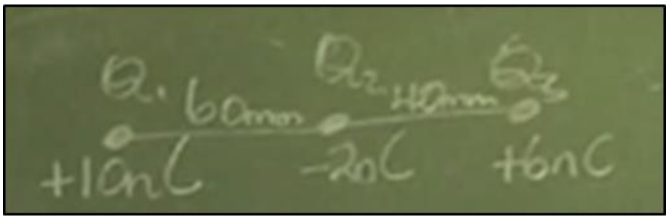



*Figure 5.12: One of the problems involving electrostatic forces solved by Ms SH.*

> *First things first, look at what $Q_1$ is doing to $Q_2$ and $Q_3$ is doing to $Q_2$. The force between $Q_1$ and $Q_2$ is it a repulsive force or attraction force? [Learners; attraction] They attract, so it means the*

*force on $Q_2$ will be to the left. Between $Q_2$ and $Q_3$ is it attraction of repulsion? [Learners; attraction]. In which direction will the force face?[Learners: Left] [After the individual forces had been calculated] now you have these two forces. The other one is acting to the left, and the other one is acting to the right. So to find $F_{net}$, $F_{net}$ is equal to what? Add the two forces. Taking to the right as positive, it means everything that is going to the right has a positive sign and then to the left will be negative. This sign tells us the direction of the force. Then we get $F_{net} = 1.75 \times 10^{-5}$ N to the right because we said take right as positive.* (Ms SH)

She also specified the directions of the separate forces and a frame of reference that she used to add them to obtain their resultant. When solving 2D problems, Ms SH made several alterations to her teaching strategy when learners failed to understand some of the concepts. For example, learners failed to understand the directions of the forces and the free body diagram that represented them. As a result, she reconstructed the free body diagram, this time showing force pairs instead of just focusing on the forces acting on the reference charge. She then marked the forces acting on the reference charge as the forces of interest in the particular problem (See Figure 5.11). Similarly, she changed the position of the angle θ when she realised that learners found it difficult to identify the trigonometric function used to determine its magnitude. However, she missed the opportunity to explore learners' mathematical thinking because it seems that they regarded the vertical side as the "opposite" side regardless of the position of the angle. Thus she positioned the angle such that it matched the thinking of the learners.

The observations made reveals that some of Ms SH's strategies were adequate while others were not, for example, the drawings of some of the vectors diagrams and shifting the location of the angle to suit learners' thinking. As a result, her competence was scored at Level 2.

### 5.5.2 Second key idea: Electric field

***Learners' prior knowledge***

It was observed that Ms SH appreciated the importance of engaging with learners' prior knowledge of magnetic fields and demonstrating it by using iron filings as recommended in the curriculum. However, it seemed that Ms SH regarded a magnetic and an electric field to be the same, according to the following remark:

*I know we have all seen the electric fields…the field lines around a bar magnet. This was done in Grade 10 whereby they would put a magnet under an A4 paper, and then they sprinkle the iron filings around, and you see those field lines.* (Ms SH)

She thus revealed a misconception reported in the literature about the confusion of the two fields (e.g. Hekkenberg et al., 2015). Further evidence of this misconception emerged from the VSR interview when she said: “the introduction [of Coulomb’s law] comes from Grade 10, in Grade 10 they deal with charges, a positive and a negative charge around a magnet.” During the lesson, she referred learners to their prior knowledge of charge interactions, but this knowledge was not used to explain the direction of the electric field using a positive test charge. Instead, she used it when she explained that the “empty space” in the electric field patterns for two like charges depicts a repulsion. Based on the observations made, Ms SH’s competence was scored at Level 1 not only because of her misconception that could have been transferred to the learners, but also not using the prior knowledge to explain the direction of electric fields.

***Curricular saliency***

As indicated earlier, Ms SH reminded learners of the demonstration of magnetic field lines depicted by iron filings that was done in the previous school grades. However, she did not use this prior knowledge as the foundation for the development of the concept of an electric field. Instead, she read the description of an electric field from the textbook. It was also observed that she did not discuss the concept of a positive test charge and its use in this topic. As such, she told learners about the direction of an electric field; that is, it is away from a positive charge and towards a negative charge. Seeing that she excluded the concept of a positive test charge in her lesson, I asked her to indicate why. She replied:

> *We are following the ATP (Annual teaching plan) and the work schedule, which guides us what needs to be taught and what should be excluded. So before we start with electric fields, you already know that learners must know definition ya [of an] electric field, learners must know what a test charge is. Some of the things they are just extras because I know they have learned them in Grade 10. It will also help them in Grade 11 because in Grade 11 they are not taught, but they are examinable.* (Ms SH)

She revealed a weakness in her knowledge of the curriculum because the idea of a positive test charge is discussed for the first time in Grade 11 according to the Curriculum (DoBE, 2011). While she excluded some of the concepts prescribed for this key idea in the curriculum, she discussed a concept that was beyond the scope of the curriculum – the electric field between two parallel plates. Although discussing concepts that are beyond the scope of a curriculum does not necessarily imply a weakness, what you do with the concepts counts. In Ms SH's case, the concept of electric fields between parallel plates was read from the textbook as it is for the learners. She missed an opportunity to emphasise the link between the electric field strength and the density of field lines. For parallel plates, the electric field is uniform; thus the field lines are parallel whereas it weakens with distance, shown by spreading lines around a point charge.

Ms SH's competence was scored at Level 1 because she did not show links between concepts; instead, she presented new knowledge without explaining how it came about.

***What is difficult to teach?***

How Ms SH presented concepts only prevented one of the difficulties listed in the Expert CoRe from arising (see Table 5.2). She instructed learners not to draw field patterns that show touching or intersecting field lines. However, she did not provide reasons as to why field lines must not touch. It was observed that an opportunity presented itself for Ms SH to engage with the concept of the density of electric field lines concerning the magnitude of the electric field. This was when she read off the textbook that the electric field lines between parallel plates are parallel while the electric field is uniform. However, she missed the opportunity to contrast field patterns of parallel plates and point charges and how they represent the strength of the electric field. Nevertheless, because she addressed one of the difficulties that are documented in the literature, her competence was scored at Level 2.

***Representations including analogies***

As indicated earlier, Ms SH introduced this key idea by reminding learners of the demonstration of magnetic fields using iron filings performed in Grade 10. However, some of her statements were misleading as they suggested that magnetic and electric fields are the same thing. Because Ms SH did not explain the directions of electric field lines using a positive test charge, it was inevitable that the diagram that shows a source and a positive test charge would not be utilised. Such a diagram actually appeared on the smartboard as she paged through the electronic textbook. However, she ignored it and moved on to the next page. The displayed diagram showed the directions of the forces exerted on a positive test charge by a negative and a positive source charge, respectively (see figure 5.13).

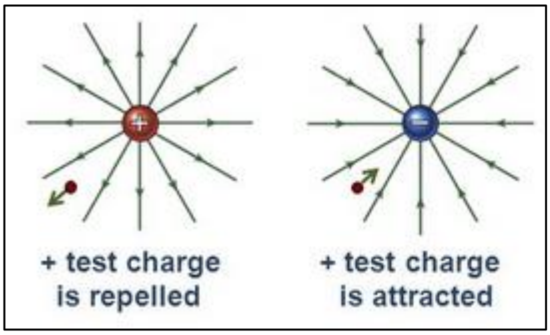



*Figure 5.13: The diagram shown on the e-book that describes the direction of the electric field which Ms SH ignored.*

Although Ms SH constructed the electric field patterns correctly, they were not based on the underlying concept that describes the direction of the electric field. As a result, Ms SH's competence was scored at Level 1.

***Conceptual teaching strategies***

Ms SH's conceptual teaching strategies were restricted in many aspects, mainly because of her apparent restricted knowledge of the content. She read concepts as they were stated in the textbooks without providing the necessary explanations and clarifications. In particular, she read the description of an electric field and that it was represented using electric field lines. Ms SH also drew the electric field patterns without making any reference to the use of a positive test charge. It is evident that Ms SH was not comfortable enough to discuss the use of a positive test charge, as explained below. She displayed a class activity on the smartboard using the electronic textbook. Learners were instructed to skip the first question that requested them to state the use of a positive test charge. However, the learners asked what a positive test charge was and how the directions of the electric field lines came about. She responded to these questions as follows:

> *[Positive test charge]: "It's a small charge that is used to determine the magnitude of the charge that is placed there [the source charge]. It is used like the controlled variable in an experiment."*
>
> *[Directions of electric field lines]: Remember an electric field is where your charge placed at one point will move. It's the direction where your charge will move. If I'm placing a negative charge here, and it's a negative charge, they say the electric field goes…meaning the force that the charge is experiencing is towards the negative sign. If it's positive, then the electric field will move that direction [she used her hands to point away depicting the direction of the electric field around a positive charge].* (Ms SH)

The responses were confusing and unclear at best, and they did not answer the questions asked. Confirmation of her restricted knowledge of the content emerged from the VSR interview when I asked her to indicate how she explained the direction of an electric field:

*Interviewer: "If you could describe to me your explanations of electric fields, particularly the direction considering the fact that they are vectors."*

*Ms SH: "The direction of the electric field?"*

*Interviewer: "Ja [yes]."*

*Ms SH: "Yoh this one. E needa ke lo refera again. Kgale ke di fetile and my mind e tswile mo di electric fielding. Ke busy ka chemistry nou."*

*[This one requires me to refer again. It's been a while since I moved past electric fields and my mind has forgotten about them. I'm currently busy with chemistry]*

*Interviewer: "If that's the case, then it's fine."*

Based on the observation made and the VSR interview, Ms SH's competence in terms of conceptual teaching strategies was scored at Level 1 because she read concepts from the textbook without providing any explanations.

### 5.5.3 Third key idea: Electric field strength

***Curricular saliency***

It was observed that Ms SH discussed a few concepts that are prescribed in the curriculum. The aspects that she discussed are now described. She defined an electric field ($E = F/q$) and used the definition to solve problems. The problems were already solved in the textbook as examples. She gave learners an exercise from the textbook that required them to calculate the magnitude of the electrostatic force (F) acting on a nucleus of a helium atom (q) placed in an electric field (E). The textbook also requested learners to determine the acceleration of the nucleus, given its mass using Newton's second law. This exercise was extended beyond the scope of the curriculum, which does not refer to Newton's second law in the topic of electrostatics. It seems that Ms SH was not aware of this and that she simply followed the textbook.

Ms SH was also observed combining the definition of the electric field ($E = F/q$) with Coulomb's law to deduce the formula $E = k\,\frac{Q}{r^2}$ as required by the curriculum. She also used the formula to solve problems involving isolated source charges only. Furthermore, while she solved problems involving isolated charges, she did not specify the directions of the electric fields that they set up at particular points. The aspects that she did not discuss included the superposition of electric fields, as required by the curriculum. She predominantly focused on getting learners to calculate a particular variable when others are given. As a result of displaying poor knowledge of the curriculum, her competence was scored at Level 1.

***What is difficult to teach?***

It was observed that Ms SH presented new knowledge in a manner that did not prevent most of the learners' typical difficulties listed in the Expert CoRe (see Table 5.2). As she read through the textbook, she came across concepts that could have been clarified to prevent potential difficulties. However, she missed the opportunities to explain the concepts as she continued to read the concepts from the textbook. She came across the following two statements:

> *[First statement]: "A strong electric field exert a stronger force than a weak one does. If we know the electric field strength or the intensity, then we can calculate the force on any charge placed in the field"* (*Ms SH).*
>
> *[Second statement]: "A unit charge is a charge on one coulomb, q Is a charge placed at a point in the field, it is not the source of the field" (Ms SH).*

Both statements could have been clarified to show learners that the magnitude of the test charge does not influence the magnitude of the electric field at any point. Nevertheless, she attempted to explain the application of the formula $E = k\frac{Q}{r^2}$. She mentioned that the formula is used "if you are given a charge placed at a distance". This statement is unclear and suggests that there has to be a charge at a point when the magnitude of an electric field at that point is calculated, which is a misconception related to the confusion of the source and the test charge (Bohigas & Periago, 2010). Nevertheless, she instructed learners not to include the signs of charges when calculating the magnitude of an electric field:

> *You never include the sign when you calculating either Coulomb's law or the electric field, you never include the sign. The sign just tells you which charge it is, electron or proton. You can't get a square root of a negative number, e tlo gofa error [it will give you an error].* (Ms SH)

It is evident that she indicated the meaning of the signs of the charges sufficiently/ However, the last statement was purely algorithmic. Nevertheless, because she addressed one of the difficulties despite missing opportunities to address others, her competence was scored at Level 2.

### *Representations including analogies*

It was evident that Ms SH missed several opportunities to utilise representations for various purposes in her lesson. For example, she derived the formula $E = k\frac{Q}{r^2}$ out of context as she did not construct a suitable diagram showing a source and a test charge. As indicated earlier, Ms SH ignored such a diagram when it appeared on the smartboard. How she solved problems emphasised algorithms rather than conceptual understanding. As a result, suitable drawings were not used to contextualise the problem and to support how she solved them. Instead, she listed the variables that were given and substituted them into a suitable formula to determine the magnitude of the unknown variable. According to the evaluation criteria, the fact that Ms SH did not use representations corresponds with a score of Level 1.

### *Conceptual teaching strategies*

Ms SH's teaching strategy was a lecture method because she read concepts as they were stated in the textbook without providing clarifications and explanations. Furthermore, the strategies promoted algorithms rather than conceptual understanding. The problems that Ms SH solved were actually given as examples with solutions in the textbook, and they all involved isolated source charges. The first example involved a negative charge that was placed in an electric field of an unidentified source charge. The magnitude of the negative charge and that of the force acting on it, including its direction were given. Ms SH listed the information that was given and wrote down the suitable formula *E* = *F/q*:

> *Ms SH: Are you going to use a negative or a positive charge…and why? [As the given charge was negative, she was asking if learners are going to include the negative sign or not when calculating the electric field strength using $E = \frac{F}{q}$]*
>
> *Learners: "Positive [according to the majority of the learners]."*
>
> *Learner A: Ma'am, e ya downwards [Madam, it is going downwards]*
>
> *Ms SH: "It's going downwards? [She did not follow up on this question] Why positive, why are we not using negative, why are we not including the sign of the charge?"*
>
> *Learner A: "The sign e re bontsa direction [the sign shows us the direction]."*
>
> *Ms SH: "Thank you, because the sign will show us the direction of the field."*

Learner A indicated the correct direction of the electric field because the problem was taken as-is from the textbook with solutions. Ms SH did not, however, acknowledge the answer and did not allow the learner to substantiate it. Although the direction of the electric field was indicated in the example, Ms SH did not indicate it in her calculation, and she did not comment on it, as seen in the dialogue above. She could have explained that since the force acting on the negative charge was upwards, the charge was either repelled by a negative charge underneath or attracted by a positive charge above it. A suitable drawing of either or both cases would have also helped learners visualise the problem and clearly indicate why the electric field is downwards. The way she solved problems using the formula for a point charge as a source of the field was not different as diagrams were also not utilised, and the directions of the fields were not determined. As a result, Ms SH’s competence was scored at Level 1, not only because her strategies lacked the use of representations and explanations, but also because they promoted algorithmic thinking.

## 5.6 CASE STUDY FOUR – MR PM

At the time of this study, Mr PM was the head of the department of physical sciences in his school. He was also involved in the marking of Grade 12 physical sciences national final examinations. As indicated earlier, Mr PM did not avail himself when he was invited for a VSR interview. As a result, the discussion of his enacted knowledge is based on the observations of his lessons only. The scores allocated for his competences in the components of PCK for each key idea are summarised in Table 5.6. These scores are then discussed per key idea.

*Table 5.6: Mr PM's allocated scores reflecting his enacted PCK.*

| **TSPCK component** | **Electrostatic force** | **Electric field** | **Electric field strength** |
|---|---|---|---|
| Learners’ prior knowledge | 3 | 1 | – |
| Curricular saliency | 3 | 2 | 2 |
| What is difficult to teach? | 2 | 1 | 2 |
| Representations including analogies. | 3 | 2 | 3 |
| Conceptual teaching strategies | 3 | 2 | 2 |
| **Average score** | **2.8** | **1.6** | **2.25** |

### 5.6.1 First key idea: Electrostatic force

***Learners' prior knowledge***

Mr PM used the first lesson that he presented under my observation to reteach the majority of the concepts of electrostatics that are prescribed for Grade 10 learners in the curriculum. The concepts included the two kinds of charges, a positive and a negative charge as well as their corresponding subatomic particles. He also reminded them about the comparison of the number of the subatomic particles in a positive, a negative and a neutral object. Furthermore, he reminded learners about the law of conservation of charges and confirmed it with a calculation of the number of electrons transferred between two objects that are in contact. When teaching new knowledge, he uncovered learners' understanding of the corresponding prior knowledge using guiding questions. For example, this is how he uncovered learners' understanding of Newton's third law:

> *We want these two [spheres] to touch, and they will touch because they will attract. The force that we are talking about here is the electrostatic force. Now that the charges are unlike, the nature of the force between them will be an attraction. What does that mean? It means that sphere A will exert a force on sphere B. The force that sphere B will exert on sphere A will be of the same magnitude but different direction. Which law of Newton confirms that?*

Similarly, he reminded learners that a force is a vector quantity and only asked them to describe the features of a vector quantity. Nevertheless, he checked whether learners understand that when drawing a free body diagram, a dot is used to represent the object while the forces are constructed away from the dot. Furthermore, he uncovered their understanding of a resultant vector and how such a vector is constructed in 2D problems. Because Mr PM uncovered most of the relevant prior knowledge through questions, he was allocated a Level 3 score.

***Curricular saliency***

Mr PM's lessons revealed that he discussed the majority of the concepts that are prescribed for this key idea in the curriculum. Whenever he discussed an idea that relates to learners' prior knowledge, he engaged briefly with the knowledge. For example, he related Coulomb's law with Newton's law of universal gravitation by outlining their similarities and differences. He also obtained the directions of the forces acting on the reference charge from the prior knowledge of charge interactions. The forces were also represented using vector diagrams that were drawn relative to their anticipated magnitudes. However, the magnitudes were deduced from the relationship between the electrostatic force and the distance between charges. Thus the force exerted on the reference charge by the closest charge was represented using a longer vector. This notion is not entirely true and it almost resulted in an error during his lesson as will be shown later. Some of the diagrams showed force pairs which Mr PM used to emphasise the application of Newton's third law in this topic.

The sequence in which Mr PM solved problems was adequate. He specified the directions of the separate forces acting on the reference charge, for example: $F_{A \text{ on } B}$ = 62.5 N to the left. However, he did not refer learners to a frame of reference. Instead, he added the separate forces accordingly to obtain their resultant in terms of the magnitude and direction. When solving 2D problems, he referred learners to their prior knowledge and skills including the parallelogram method, the theorem of Pythagoras and trigonometric ratios.

It was evident from Mr PM's lessons that he emphasised aspects of this key idea that are assessed in examinations. For example, he specified the keywords that are awarded marks when stating Coulomb's law. Furthermore, he indicated the mark allocation whenever he solved problems by ticking the relevant items while explaining the reasons for granting such a mark. Nevertheless, how he linked prior knowledge with new concepts and the sequence in which the concepts were presented was adequate. As a result, he was allocated a Level 3 score in this component.

***What makes it difficult to teach this idea?***

The observations made revealed that Mr PM presented concepts in a manner that prevented some difficulties while encouraging others. It was observed that Mr PM referred to the inverse square relationship between force and distance whenever he constructed free body diagrams. As such, the force exerted by the closest charge to the reference was represented with a longer vector. As indicated earlier, it is not always the closest charge that exerts a stronger force, and as such, his problem-solving approach had the potential to induce difficulties.

When calculating the magnitude of the electrostatic force, Mr PM instructed learners not to include the sings of charges when substituting into Coulomb's law. The reason for the exclusion of signs was however, not indicated until one learner asked about it when Mr PM was already solving the second problem:

*Learner A: "Why doesn't the answer have a negative sign?" [She was asking why he excluded the sign in the previous calculation]."*

*Mr PM: "Kana [by the way] negative and positive tell us about what?"*

*Learners: "Direction."*

*Mr PM: "They tell us about the nature of the force, so it means the force is attraction. We have accounted for that negative sign."*

The signs that Mr PM was referring to were the polarity of the charges, not vector characteristics. He did not rephrase the question even though learners immediately thought of the signs in terms of direction.

Because Mr PM addressed the challenge associated with the substitution of charges inadequately, and the fact he drew vector diagrams following an approach that may cause difficulties resulted in his competence being scored at Level 2.

***Representations including analogies***

As indicated earlier, Mr PM used the first lesson to reteach Grade 10 concepts of electrostatics. However, he did not use representations to engage with the prior knowledge except for when he explained the application of Newton's third law in electrostatic forces. In this regard, he drew arrows of equal lengths showing the forces that the charges exerted on each other. However, the labels on the forces were often swopped (See Figure 5.14).

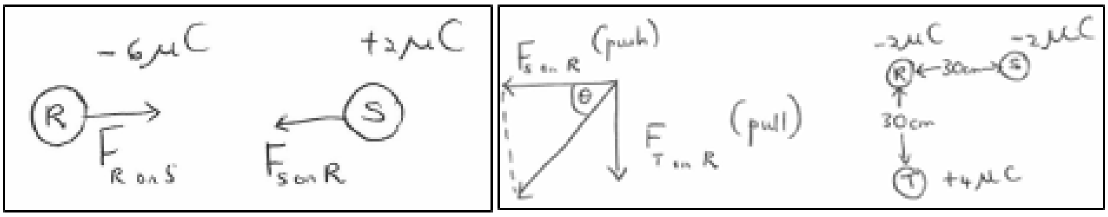



*Figure 5.14: Some of the diagrams used by Mr PM when solving problems involving electrostatic forces.*

Nevertheless, he constructed and labelled free body diagrams correctly while using different colours. The labels clearly indicated the object that exerted the force and the object that experienced it, for example, $F_{S\ on\ R}$. Furthermore, the vectors were constructed relative to their anticipated magnitudes according to the relationship between force and distance only. Having emphasised the fact that a force is a pull or a push, Mr PM included these words in some of the diagrams to help them conceptualise the effects of the attractive and repulsive forces on the reference charge. Regarding 2D problems, Mr PM presented the forces in a tail-to-tail configuration which he did not change into a head-to-tail. Instead, he drew a dotted line that joined the arrowhead of the horizontal force and that of the resultant force (See Figure 5.14). The resulting diagram was labelled accordingly with Mr PM placing x, y and r on the corresponding sides of the triangle to show learners how they fit into the theorem of Pythagoras. Based on the gathered data, it was evident that Mr PM used the same kind of representations (drawings) to support the development of various concepts related to electrostatic forces. As a result, his competence was scored at Level 3.

***Conceptual teaching strategies***

Mr PM's teaching strategies were largely characterised by questions, explanations and representations. However, some of the questions presented most of the crucial information while learners had to state the rest. For example, he asked: "the two objects exert the same force on each other in opposite directions, which law of Newton confirms that?" When solving problems, he combined a variety of concepts and skills. He instructed learners to study the interactions between charges to obtain the directions of the forces acting on the reference charge, which he represented using vector diagrams. He also described a force as a pull or a push action and used those actions to describe an attraction and repulsion, respectively. As indicated earlier, the vector diagrams were constructed based on their anticipated magnitudes according to the relationship between force and distance only. This approach almost resulted in an error in one of the problems that he solved (See Figure 5.15).

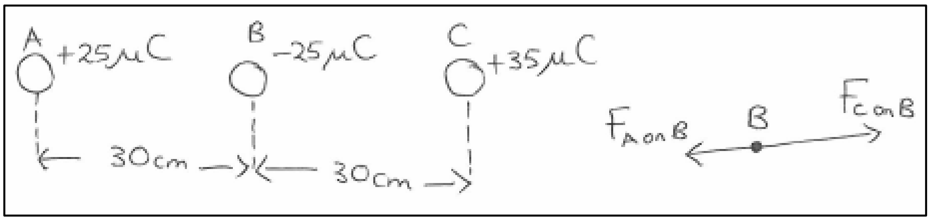



*Figure 5.15: The first problem involving electrostatic forces solved by Mr PM.*

Before calculating the magnitudes of the forces, Mr PM instructed learners to study the interaction between two charges at a time. This is how the discussion went.

> *Mr PM: Do you agree with me that A will pull B? Remember a force is a pull or a push. Pull is an attraction, right? In which direction does it pull it, left or right? This one will be $F_{A\ on\ B}$ because A*

*is the one that is doing the pulling. The other one, on the other side, of exactly equal magnitude because distance is the same…even… [He stopped talking upon realising his mistake]*

*Learner A: Sir, ka gore di charge ga di tshwane, doesn't it mean force ya C e tlaba e golo nyana? [Sir, given the fact that the charges are not the same, doesn't it mean that the force exerted by C will be slightly longer?]*

*Mr PM: "Yes this one [$F_{C\ on\ B}$] will be a little bit longer than this one [$F_{A\ on\ B}$]."*

Although Mr PM rectified his mistake, he still focused on the relationship between the force and distance when solving the rest of the problems. Before calculating the net force, he also asked one of the learners to define a resultant vector and emphasised the fact that the word "net" describes a sum. He then wrote a mathematical expression of the net force and substituted the forces to the left and the right as positive and negative respectively without a reference frame:

*Learner A: "Meneer [Sir], $F_{A\ on\ B}$ is to the left, it should be minus [negative]. [Other learners responded, telling Learner A that it is fine the way it is])."*

*Mr PM: Leave him alone [Instructing the other learners]. We can also write it in this way; we can say $F_{C\ on\ B}$ + (- $F_{A\ on\ B}$). He wants it in this order because he refers to the Cartesian plane where right, most of the time means positive and left means negative. So he wants to organise his thinking along those lines, so let's leave him, that's how he will get it right. Ultimately we will get the same answer.*

Mr PM calculated the net force using both expressions and interpreted the direction accordingly in both cases. How he solved 2D problems was almost similar to the one described above. Because most of the concepts were explained adequately using fruitful strategies, Mr PM's competence was allocated a Level 3 score.

### 5.6.2 Second key idea: Electric field

***Learners' prior knowledge***

In his discussion of this key idea, Mr PM did not uncover learners' prior understanding of aspects of magnetic fields that are related to those of electric fields. As such, he missed an opportunity to uncover learners' understanding of fields in general and their representations using field lines. Nevertheless, he referred learners to their prior knowledge of charge interaction which he used to explain the direction of the electric field at a point using a positive test charge. However, because he disregarded the prior knowledge of magnetic fields, his competence was scored at Level 1.

### *Curricular saliency*

Mr PM's lessons revealed that he discussed some of the concepts that are prescribed for this key idea in the curriculum. As indicated earlier, he did not relate the concept of an electric field with the prior knowledge of magnetic fields. Nevertheless, he adequately used the prior knowledge of charge interactions to explain the direction of an electric field as the path taken by a positive test charge when it is attracted or repelled by a negative and positive source charge respectively. It was this link between prior knowledge and new concepts that resulted in a Level 2 score for Mr PM's knowledge of curricular saliency.

### *What is difficult to teach?*

It was observed that Mr PM did not uncover or address any of the difficulties listed in the Expert CoRe (see Table 5.2). The way he drew electric field patterns had the potential to induce a misunderstanding of how these patterns should be drawn (See Figure 5.16).

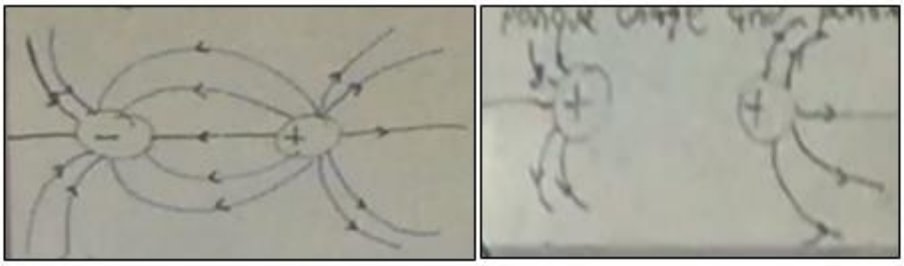


*Figure 5.16: Mr PM's drawings of electric field patterns.*

Firstly, the field lines extending from the positive point charge in the diagram on the left were touching. Secondly, the curvature of some of the electric field lines between the two positive charges in the diagram on the right was asymmetrical and thus did not correctly reflect the resultant nature of the electric field. Mr PM's competence was thus scored at Level 1 because he did not address any potential difficulties while he drew field patterns incorrectly.

### *Representations including analogies*

It was observed that Mr JM used a single representation, drawings, to support the discussion of the direction of an electric field at a point and electric field patterns. He drew a diagram showing a source charge and a positive test charge labelled +1C next to it (See Figure 5.17). He also indicated the path taken by the positive test charge using an arrow while emphasising that it represented the direction of the electric field at that point.

*Figure 5.17: The diagrams used by Mr PM to obtain the directions of electric fields.*

The drawings of the electric field patterns for various configurations of charges were also based on these diagrams, that is, electric field lines point away from a positive and towards a negative charge. Because Mr PM only used one representation to support his discussion of concepts, he was allocated a Level 2 score.

***Conceptual teaching strategies***

Mr PM's conceptual teaching strategies were largely characterised by questions and explanations. When he introduced the concept of an electric field, he clarified the distinction between its description (the region of space where a charge experiences a force) and its definition (force per unit charge). He then wrote the underlying concept that describes the direction of an electric field on the board as "the direction of the electric field at a point is the direction that a positive test charge would move if placed at that point". This information was used alongside drawings of a source and a positive test charge to facilitate the discussion of the direction of an electric field, as shown in the following conversation:

> *Mr PM: "If I have a positive charge [while drawing it], and I want to know the direction of the electric field, what do I do?"*
>
> *Learner A: You put a test charge [Mr PM placed it next to the positive charge that he drew earlier]. The direction that the test charge would move to, then it's the direction of the electric field.*
>
> *Mr PM: "Ok, what is the nature of the force between this charge [the source charge] and the test charge?"*
>
> *Learners: "Repulsion."*
>
> *Mr PM: Repulsion neh [right]? This then means this charge will move in this direction [while drawing an arrow show the path]. Akere [isn't it] they will repel? So it means the direction will be outwards.*

*Learner A: "Ohoo so this is how they draw them? Because in the negative they [field lines] go towards."*

*Mr PM: "Yes, because negative and positive attract."*

The questions he asked required learners to apply their prior knowledge of charge interactions. As indicated earlier, the drawings of the electric field patterns were also based on this discussion.

Although the direction of the electric field was explained thoroughly, the electric field patterns were drawn inadequately. Furthermore, Mr PM did not refer to the concept of magnetic fields to support learners' conceptualisation of fields. Based on the observations made, he was allocated a Level 2 score.

### 5.6.3 Third key idea: Electric field strength

***Curricular saliency***

It was observed that Mr PM discussed most of the concepts that are prescribed for this key idea in the curriculum. However, he did not appreciate the importance of deriving the formula $E = k\frac{Q}{r^2}$ to show learners how it links with the prior knowledge of Coulomb's law and the definition of an electric field (*E = F/q*). Instead, the formula was given to the learners as it is:

> *You have the distance between these two [the source and the positive test charge] right? It means you can calculate the electric field…the second thing that they will ask you to do is to calculate the electric field at a point due to a number of charges. The formula that we use is $E = k\frac{Q}{r^2}$. Do not confuse this formula with the formula for F [$F = k\,\frac{Q_1Q_2}{r^2}$].* (Mr PM)

Mr PM immediately used the formula to solve problems pertaining to the superposition of electric fields without allowing learners to grow into the concept by starting with isolated charges. Nevertheless, he showed links between some of the new concepts and their corresponding prior knowledge. He obtained the direction of the electric field at a point by placing a positive test charge at that point and asked learners to study its interaction with each of the source charges. The way he solved problems showed connections between the individual fields and their resultants. He indicated the directions of the fields in writing next to their magnitudes. He also chose a reference frame and formulated a mathematical expression that he used to obtain the magnitude and the direction of the resultant electric fields. Based on the observations made, Mr PM's knowledge of curricular saliency for the electric field strength was scored at Level

2 mainly because, although he solved problems adequately, he did not derive the formula $E = k\frac{Q}{r^2}$.

***What is difficult to teach?***

It was observed that Mr PM seldom presented concepts in a manner that prevented the difficulties listed in the Expert CoRe from arising (see Table 5.2). He only instructed learners not to substitute the signs of charges when calculating the magnitude of the electric field. After having calculated the electric field set up by a positive charge, he went on to determine the electric field set up by a negative charge at the same point (refer to Figure 5.18):

> *Now the other one will be $E = k\frac{Q_2}{r^2}$, no mark for this. Other learners sometimes they substitute the negative right? And we spoke that the negative you don't substitute it right? When you perform your calculations you omit the negative because e re botsa ka direction ya electric field [it tells us about the direction of the electric field].* (Mr PM)

Although Mr PM instructed learners not to substitute the signs of the charges, he did not refer to the possible misinterpretation of the negative sign. He also mentioned that the negative sign represents the direction of the electric field, a statement that could be interpreted incorrectly by learners. Based on the fact that he attempted to prevent one of the challenges from arising, his competence was scored at Level 2.

***Representations including analogies***

It was observed that Mr PM used drawings as part of his problem-solving technique. He drew a diagram showing two source charges and the point of interest, P, where both charges set up an electric field to contextualise the problem. He then wrote a positive sign "+" next to the point of interest (see Figure 5.18).


*Figure 5.18: The diagrams used by Mr PM to solve problems involving the electric field strength.*

The idea was that learners must imagine a positive test charge placed at that point. Mr PM then prompted learners to study the interactions between the positive test charge and the source charges to obtain the directions of the forces acting on the test charge. He mentioned that the direction of the force acting on the test charge is the same as that of the electric field at that point. Upon getting the directions of the fields, he used drawings of vector diagrams to represent the electric fields. The vectors were also labelled accordingly, for example, "$E_{Q1 \text{ at } P}$" to specify the source charge that set up the electric field represented by the respective vector at that point. Furthermore, the vectors were constructed relative to their anticipated magnitudes according to the inverse relationship between distance and the electric field strength. Although he only used drawings when he was solving problems, the purpose of the drawings was evident. As a result, his competence was scored at Level 3.

***Conceptual teaching strategies***

Mr PM's conceptual teaching strategy was largely influenced by explanations and representations. The strategies were only evident when he solved problems as he did not derive the formula $E = k\frac{Q}{r^2}$. Furthermore, he immediately solved complex problems of field superposition without starting with basic problems to allow learners to grow into the techniques used to determine the magnitude and the direction of electric fields set up by isolated charges. As such, he did not explain the role of the source charge (Q) and distance (r) concerning the electric field strength (E). Nevertheless, the electric fields set up by two source charges as well as their resultant were adequately discussed as shown below (refer to Figure 5.18):

> *Mr JM: By the way what you can do from the previous lesson. You can calculate the magnitude of the electrostatic force and the new charge after they have made contact. Additionally, you can calculate the electric field at P. Remember P will be a positive test charge. When I'm looking for the electric field at P as a result of $Q_1$ and $Q_2$, can you see that $Q_1$ will repel P?*
>
> *Learners: "Yes."*
>
> *Mr PM: "The direction of the electric field is the direction of the force. $Q_1$ will push P. What will happen with $Q_2$?"*
>
> *Learners: "It will attract".*
>
> *Mr PM: "The formula that we use is $E = k\frac{Q}{r^2}$. Do not confuse this formula with the formula for F [$F = k\ \frac{Q_1Q_2}{r^2}$]."*

Mr PM referred learners to the content that was covered in the previous key idea. He placed a positive sign near the point of interest such that it represents a positive test charge. He also requested learners to study the interactions between the source charges and the positive test charge so as to obtain the directions of the electric fields set up by the source charges. He also constructed electric field vector diagrams relative to their anticipated magnitudes. As indicated in the first key idea, this is dangerous considering that the closest charge can set up a weaker electric field compared to a distant charge if it is significantly big. The vectors were also labelled in such a way that indicated the source charge that set up the electric field at that point, for example "$E_{Q1 \text{ on } P}$". As indicated earlier, he determined the magnitude and direction of the resultant electric field adequately. He specified the directions of the separate fields in writing and decided on a reference frame that he used to formulate a mathematical expression for the resultant field. Thus it is noted that his problem-solving techniques were adequate, except for the fact that he disregarded the influence of charge size on the magnitude of an electric field when he constructed vector diagram in proportion to the anticipated magnitudes of the field. Furthermore, he did not derive the formula $E = k\frac{Q}{r^2}$. According to the observations made, Mr PM's competence was thus scored at Level 2.

## 5.7 CHAPTER SUMMARY

In this chapter, I presented and analysed data that reflected teachers' enacted PCK about electrostatics at concept specific level. The data was collected using classroom observations and VSR interviews. A rubric developed for enacted PCK was used to quantify the competence of the teachers in the five components of PCK on a four-point scale. The allocated scores were then averaged to obtain an overall score that reflects the PCK of the teachers in the key ideas. In the next chapter, I will present and analyse data that reflected the performance of the learners.

# 6. CHAPTER SIX: LEARNERS' PERFORMANCE IN ELECTROSTATICS

## 6.1 INTRODUCTION

This chapter presents and describes the interpretation of the data that was collected from the participating learners using a baseline (see Appendix iv) and a Grade 11 performance test (see Appendix vi). The main focus of this chapter is the performances of learners in the Grade 11 test as these will be related to the PCK of the participating teachers in the next chapter. In the current chapter, the data obtained from the Grade 11 test will be presented and explored within the boundaries of the key ideas that framed the PCK of the participating teachers. Learners' typical mistakes in the test are also explored as they may be related to gaps in their teachers' PCK.

## 6.2 LEARNERS' PERFORMANCE IN THE BASELINE TEST

As mentioned in the third chapter, all the participating learners wrote a baseline test that explored their understanding of electrostatics concepts taught in Grade 10 (see Appendix iv). The test was administered to assess learners' knowledge of electrostatics before they were taught new concepts of electrostatics that are prescribed for Grade 11 in the curriculum. Table 6.1 presents the average performances of the learners in the baseline test.

*Table 6.1: Participating learners' average performance in the baseline test.*

| Teachers | Type of school | Number of learners taught | Average performance |
|---|---|---|---|
| Ms VK | Adequately resourced | 25 x 2 classes | 44.80% |
| Mr JM | Poorly resourced | 23 | 38.72% |
| Ms SH | Poorly resourced | 23 | 34.94% |
| Mr PM | Poorly resourced | 38 | 45.65% |

As shown in Table 6.1, the four groups of learners all performed below 50%, with average scores ranging between 35% and 46%. It is evident that the learners were able to recall some of the grade 10 concepts of electrostatics. These included the unit of measurement of a charge, the sign of the charge of a proton, the nature of charge interactions and conductors. Furthermore, most of the learners were able to contrast the number of protons and electrons in a charged or neutral object. However, they faced challenges in the questions that focused on charge quantisation, polarisation and electron transfer. Hence the overall performance across the classes was below 50% following that the questions that were challenging for learners were allocated the most marks (See Appendix iv).

## 6.3 LEARNERS' PERFORMANCE IN ELECTROSTATICS

The overall test scores obtained by the participating learners are summarised in Table 6.2. Included in the table are the scores obtained within the same key ideas that framed the PCK of the participating teachers.

*Table 6.2: Participating learners' average performance in the key ideas and overall performance in the Grade 11 test.*

| Teachers' identities | Electrostatic force $\bar{x}$ (%) | Electric field $\bar{x}$ (%) | Electric field strength $\bar{x}$ (%) | Overall $\bar{x}$ (%) |
|---|---|---|---|---|
| Ms VK | 61.0 | 60.9 | 45.3 | 55.7 |
| Mr JM | 49.8 | 59.1 | 32.8 | 46.1 |
| Ms SH | 26.5 | 42.5 | 13.4 | 25.6 |
| Mr PM | 57.1 | 52.1 | 36.3 | 49.1 |

As shown in Table 6.2, Ms VK's learners obtained the highest overall average score while those of Ms SH scored the lowest. Furthermore, the average scores of the learners in each school varied across the key ideas. Generally, the concept of the electric field strength was relatively difficult for learners across the schools compared to the other key ideas.

### 6.3.1 First key idea: Electrostatic force

The performances of the learners in the test items that explored aspects of the electrostatic force are summarised in Table 6.3.

*Table 6.3: Learners' average performance in the questions about electrostatic forces.*

| Teacher's | Average scores obtained in the test questions (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| identities | Q1.1 | Q1.2 | Q1.3 | Q1.5 | Q2.1.1 | Q2.1.2 | Q2.1.3 | Q2.1.4 | Q2.1.5 |
| Ms VK | 84.0 | 44.0 | 14.0 | 46.0 | 82.7 | 90.7 | 30.0 | 86.0 | 30.0 |
| Mr JM | 86.4 | 45.5 | 13.6 | 22.7 | 71.2 | 63.6 | 27.3 | 47.7 | 40.9 |
| Ms SH | 34.8 | 4.35 | 26.1 | 8.70 | 66.7 | 42.0 | 8.70 | 8.70 | 2.17 |
| Mr PM | 73.7 | 47.4 | 15.8 | 26.3 | 90.4 | 73.7 | 47.4 | 60.5 | 48.7 |

As shown in Table 6.3, the overall performances in the test items that explored different aspects of the electrostatic force varied. The majority of the learners could state Coulomb's law in words in Question 2.1.1. Furthermore, most of them understood the relationship between the magnitudes of charges and the electrostatic forces between them in Question 1.1. When the magnitude of one of two interacting charges was increased by a factor of four, the majority of the learners understood that the force between the charges became four times stronger. However, responses to Question 1.2 revealed that their understanding of the relationship between distance and the electrostatic force was restricted. When the distance between two interacting charges was doubled, some of the learners thought the force either weakened by a factor of a half while others believed that it strengthened by a factor of four. The misunderstanding of the relationship between the electrostatic force and distance was also reported in the study by Maloney et al. (2001) using the same test item.

The participating learners were also tested in terms of the ability to apply Coulomb's law to solve problems based on the diagram in Figure 6.1.

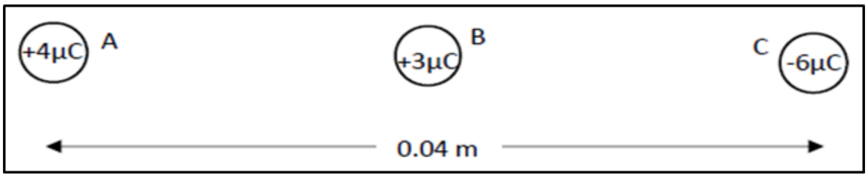



*Figure 6.1: The diagram used in Question 2 of the performance test.*

In Question 2.1.2 and 2.1.4, learners were requested to determine the magnitude and the direction of the electrostatic forces exerted by sphere A and sphere C on sphere B, respectively. As shown in Table 6.3, learners performed better in Question 2.1.2 than they did in 2.1.4. The reason for this difference is that learners were awarded marks for writing down the correct formula for calculating the electrostatic force (Coulomb's law) in Question 2.1.2, which was not the case in Question 2.1.4. Many of the difficulties that were revealed by the learners were technical issues while others were conceptual. For example, some of the learners wrote down Coulomb's law with the two charges added instead of being multiplied. It was also found that some of the learners failed to convert the units of charges while others substituted the charges and the distance as they were given. Nevertheless, it was evident that most of the learners did not substitute signs of charges into Coulomb's law, which is the correct way to determine forces.

It was evident that some of the learners studied the interactions between charges since they wrote them down when asked to indicate the directions of the forces. The marking system used in the study allowed learners to be awarded marks if the interactions were correct. However, it was evident that some of the learners failed to interpret the interactions when they were requested to superimpose the forces in Question 2.1.5. Many of the learners thought that an attraction and repulsion necessarily represent forces that are in opposite directions. As such, they subtracted the two forces. However, looking at the diagram in Figure 6.1, sphere B is attracted and repelled in the same direction by sphere C and A, respectively. Furthermore, some of the learners indicated the direction of the resultant forces by describing charge interactions, for example, $F_{net}$ = 675 N attraction. Such responses provided further evidence of the fact that some of the learners associated the charge interactions with the positive and negative directions. A different type of mistake was learners using Coulomb's law to determine the resultant force using the formula $F_{net} = k\frac{Q_2Q_1}{r^2}$, while others used the theorem of Pythagoras, not realising that the two forces were in a single dimension.

Obtaining the direction of the resultant force in 2D was also problematic for learners, as shown by their performance in Question 1.5 (see Figure 6.2).

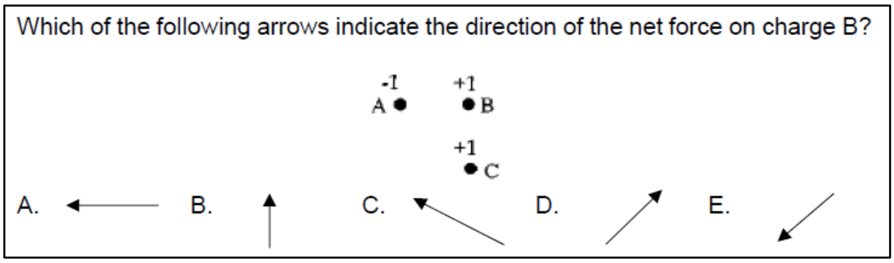



*Figure 6.2: One of the questions used to test learners' understanding of resultant force in 2D*

The results showed that some of the learners disregarded the fact that the reference charge experienced two forces along the horizontal and the vertical axes. This inference is based on the fact that many of the learners selected vector diagrams that were either horizontal or vertical instead of choosing the correct two-dimensional vector diagram.

The application of Newton's third law in electrostatic forces also proved to be difficult for the majority of the participating learners. In Question 1.3, which was a multiple-choice item, learners were given a diagram showing two oppositely charged spheres with unequal magnitudes (+Q and – 2Q). The question requested learners to select the option that shows the correct pair of vectors that represented the forces that the charges exerted on each other. It was evident that most of the learners understood the nature of the interaction between the charges as they selected diagrams showing vectors that were pointing towards each other. However, they selected options that contained vectors of unequal lengths. The quotes below indicate how some of the learners explained their selection of the vectors with unequal lengths:

> *Learner A: "The charges are unlike and therefore will attract one another, but the greater attraction will come from Y because Y has a greater negative charge compared to X."*
>
> *Learner B: "Because the magnitude of the charge determines the size of the force and the sign of the charge determines the direction the vector will face."*

The belief that bigger charges exert stronger forces is well documented in the literature (e.g. Ajredini et al., 2013; Bohigas & Periago, 2010; Maloney et al., 2001). Question 2.1.3 also tested learners' understanding of the application of Newton's third law. After having calculated the force exerted by sphere A on sphere B in Question 2.1.2, learners were then requested to write down the magnitude and the direction of the force exerted by sphere B on sphere A (See Figure 6.1). In contrast to responses to Question 1.3, most learners now indicated that the forces were equal in magnitude. However, many learners described the direction in terms of charge interactions; similar to what they had written in Question 2.1.2. It was therefore unclear whether or not these learners understood that the forces were in opposite directions; thus they did not get marks for the directions.

### 6.3.2 Second key idea: Electric field

The average performances obtained by the participating learners in the test items that explored aspects of the electric field are summarised in Table 6.4.

*Table 6.4: Learners' average performance in the questions about the electric field.*

| Teachers' identities | Average scores obtained in the test questions (%) | | | | |
|---|---|---|---|---|---|
| | Q1.4 | Q3.1.1 | Q3.1.2 | Q3.1.3 | Q4.1.1 |
| Ms VK | 22.0 | 75.0 | 66.0 | 84.0 | 68.0 |
| Mr JM | 50.0 | 56.8 | 50.0 | 63.6 | 68.2 |
| Ms SH | 39.1 | 41.3 | 39.1 | 43.5 | 46.4 |
| Mr PM | 26.3 | 60.5 | 56.2 | 68.4 | 57.9 |

It was evident that some of the learners that participated in this study were able to describe an electric field in Question 3.1.1, while others revealed misunderstandings. For example, some of the learners believed that ferromagnetic materials are the objects that experience electrostatic forces in an electric field. In this regard, the learners confused an electric and a magnetic field (Hekkenberg et al., 2015). It was also evident that some of the participating learners were able to draw the electric field pattern for a pair of point charges (one positive and one negative) in Question 4.1.1 (See Figure 6.5). The marking system in this regard was as follows; two marks for the correct indication of the directions of the electric field lines on the outside region of the charges and one mark for the field lines between the charges. Several errors were evident in the drawings of the learners, particularly the curvatures and the directions of the electric field lines. Furthermore, some of the learners drew vector diagrams instead of electric field patterns.

While drawing electric field patterns was not much of a challenge for some of the learners, interpreting given electric field lines was a major challenge for many. In Question 1.4, which was a multiple-choice item, learners were requested to select the option that shows the correct direction of the electrostatic force acting on a negative charge placed at point P (See Figure 6.3).

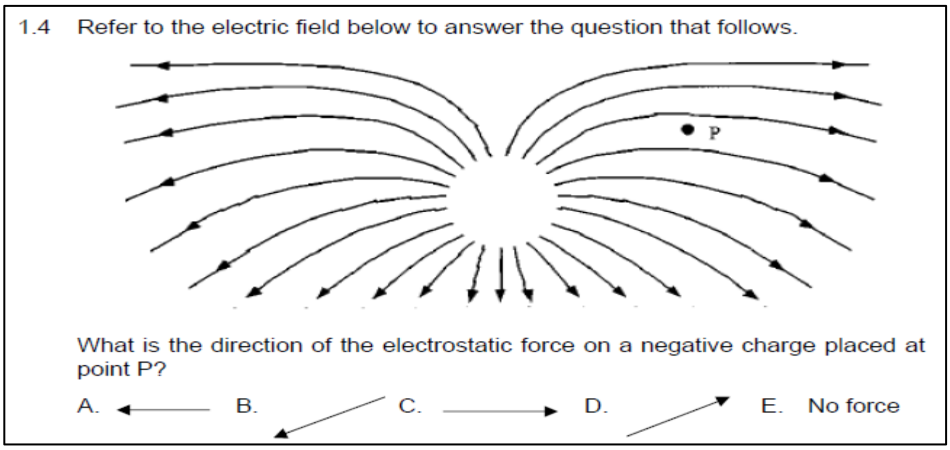



*Figure 6.3: Question 1.4 of the performance test.*

Although some of the learners selected the correct option, their reasons did not always reflect conceptual understanding. One of the learners said "because on a negative charge they move away from a negative charge" while another one wrote "because the force on a negative charge points away." Some of the learners also revealed the misconception that is reported in the literature that the electric field only exists on electric field lines and not between them (Tornkvist et al., 1993). They selected option E under the impression that the negative charge placed at point P would not experience an electrostatic force. Their reasons were as follows:

> *Learner A: "It [the negative charge] is between two lines that is why is will not experience any force."*
>
> *Learner B: "[The force is zero] because point P will not be affected."*

Other aspects of the concept of an electric field were tested using the diagram in Figure 6.4. In Question 3.1.2, learners were requested to indicate the direction of the electric field at point B. Learners were awarded marks if they wrote "left" and "towards" only.

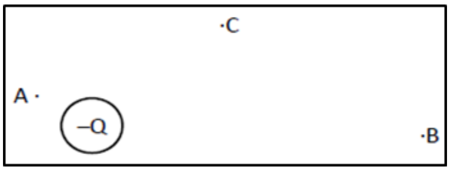



*Figure 6.4: The diagram used in question 3 of the performance test.*

Many of the learners attempted to indicate the direction by describing charge interactions, with attraction being the most popular response. Indicating the direction of an electric field at a point by describing charge interactions suggests that the learners understood the use of a positive test charge. However, there is a possibility that the learners may have considered point B to be charged, which indicates a misconception that is documented in the literature (Li & Singh, 2017). As such, they were not awarded the mark allocated for this question. The same diagram in Figure 6.3 was used to test learners' conceptual understanding of the electric field and how it weakens with distance in Question 3.1.3. Learners were asked to indicate the point where the electric field is the strongest, with many of them correctly indicating that the field is the strongest at point A.

### 6.3.3 Third key idea: Electric field strength

The average performances obtained by the participating learners in the test items that explored aspects of the electric field strength are summarised in Table 6.5.

*Table 6.5: Learners' average performance in the questions about the electric field strength.*

| Teachers' identities | Average scores obtained in the test questions (%) | | | | | |
|---|---|---|---|---|---|---|
| | Q3.1.4 | Q3.2.1 | Q4.1.2 | Q4.1.3 | Q4.1.4 | Q4.1.5 |
| Ms VK | 60.0 | 20.7 | 77.3 | 60.0 | 31.0 | 32.7 |
| Mr JM | 59.1 | 10.6 | 57.6 | 34.1 | 34.1 | 19.7 |
| Ms SH | 43.5 | 11.6 | 21.7 | 8.70 | 0.00 | 8.70 |
| Mr PM | 47.4 | 14.0 | 57.0 | 42.1 | 44.7 | 24.6 |

As indicated earlier, the concept of the electric field strength was generally difficult for participating learners. The diagram in Figure 6.4 was also used to test learners' understanding of some of the aspects of the electric field strength. In Question 3.1.4, learners were requested to indicate the point (between A, B and C) in which a test charge would experience the strongest force. It is acknowledged that this question can be answered by applying Coulomb's law. However, learners could also compare the relative electric field strengths at the locations. In comparison to the scores obtained in Question 3.1.3 in the previous key idea (see table 6.4), the results indicated that although many of the learners understood that the electric field is weak at point B, they were not aware that the same is true for the electrostatic force at that point. Although not explicit, the results suggest that the learners did not utilise the definition of an electric field ($E = F/q$) to answer Question 3.1.4.

The test results have also shown that many learners did not distinguish between the charge that creates an electric field and the one that tests the field. In Question 3.2.1, which was also based on Figure 6.4, learners were requested to calculate the magnitude of the electric field at point B. The following information was given; the magnitude of the test charge placed at point B, the magnitude of the force experienced by the test charge and its distance from the source charge. The distance was meant to distract the learners. The easiest way to calculate the electric field strength was through using the definition of an electric field ($E = F/q$). However, many of the learners calculated the electric field strength incorrectly by using the formula $E = k\frac{Q}{r^2}$ whereby they substituted Q with the magnitude of the test charge. This misunderstanding of the roles of the source and the test charge is documented in the literature (Bohigas & Periago, 2010) and has been mentioned repeatedly in diagnostic reports (for example DoBE, 2014). There were very few learners that correctly determined the electric field strength by using Coulomb's law to firstly calculate the magnitude of the source charge before substituting it into the formula $E = k\frac{Q}{r^2}$, suggesting that they understood the force concept better than the electric field concept.

The participating learners were also requested to calculate the electric fields at point X set up by charged spheres, P and Q, and to superimpose them to obtain the resultant electric field at that point (See Figure 6.5).

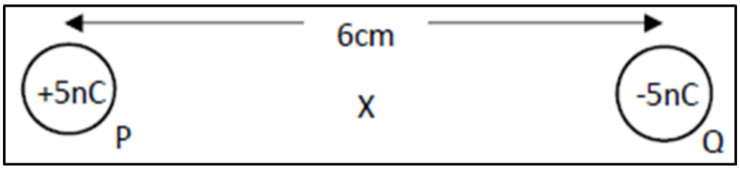



*Figure 6.5: The diagram used in question 4 of the performance test.*

Some of the challenges that the learners revealed in these questions were technical while others were conceptual. Technical challenges included the inability to convert units of the charges and the distance as well as substituting the given distance as it is without halving it. The conceptual difficulty that was common across the classes was the indication of the directions of the electric fields at point X by describing charge interactions. In this regard, the answers were marked incorrect because charge interactions suggest that point X is charged, which is a misconception (Li & Singh, 2017). However, the learners that indicated the direction as "towards Q" and "away from P" were awarded marks. The learners' ability to superimpose electric fields was explored using two further questions. Question 4.1.4 was based on the original diagram in Figure 6.5, whereas in Question 4.1.5, the negative charge, Q, was replaced with a positive charge of the same magnitude. In Question 4.1.4, learners were requested to determine the magnitude and the direction of the resultant electric field at point X, whereas, in Question 4.1.5, they were requested to state it with reasons. It was evident that learners faced difficulties even though a positive marking system was used in Question 4.1.4. The positive marking system was as follows; learners were awarded marks if they superimposed the two fields correctly, even if the separate fields were incorrect. Question 4.1.5 was treated as a free-standing item without focusing on how learners responded to the preceding questions. The manner in which learners responded to this question revealed one of the misconceptions that are documented in the literature. The misconception is the belief that the electric fields set up by like charges at any point always add up while those set up by unlike charges always cancel each other out (Li & Singh, 2017). This is how some of the learners responded to Question 4.1.5:

> *Learner A: "They [the charges] wouldn't have cancelled because they are both positive. They [the electric fields] go in the same direction."*
>
> *Learner B:" [The resultant electric field would be] +10nC, net force is a vector sum of two spheres. If both charges are positive, they add, if they are both negative, they also add and maintain the same direction, and if it is negative and positive, they subtract."*

These and many other similar responses show that the learners believed that since the charges have the same polarity, they set up electric fields that are in the same direction at any given point.

## 6.4 CHAPTER SUMMARY

In this chapter, I presented and analysed data that reflected the performance of the learners in the key ideas of electrostatics. The data were analysed collectively across the cases by looking at the successes and the challenges that learners faced in the test questions. However, the performances of the learners were averaged within their respective cases in the key ideas. This was done so that the performances could be related to the PCK of the teachers in the key ideas. In the next chapter, the PCK scores of the teachers and the performance levels of their learners are related and discussed.

# 7. CHAPTER SEVEN: THE RELATIONSHIP BETWEEN TEACHERS' PCK AND LEARNERS' OUTCOMES IN ELECTROSTATICS

## 7.1 INTRODUCTION

This chapter explores the relationship between teachers' PCK and learners' outcomes. In chapter four and five, I described the personal and the enacted PCK of the teachers, which were scored per key idea. In chapter six, I presented the average performances of the learners per key idea. In 7.2, the indicators of a relationship are investigated by calculating the Pearson's correlation coefficients for each key idea. Section 7.3 presents a qualitative discussion, providing examples that illustrate the correlation of learners' outcomes to their teachers' enacted PCK. Finally, Section 7.4 presents a discussion that compares the teachers' personal and the enacted PCK in relation to the outcomes of their learners.

## 7.2 QUANTITATIVE INVESTIGATION OF THE RELATIONSHIP BETWEEN TEACHERS' PCK AND LEARNERS' OUTCOMES

As indicated earlier, teachers' PCK was viewed as two manifestations; the personal PCK, which is static (Chan & Hume, 2019), and enacted PCK which is dynamic (Alonzo & Kim, 2016). The outcomes of the learners were separately related to these manifestations of the teachers' PCK.

### 7.2.1 Teachers' personal PCK and learners' outcomes

A summary of teachers' PCK scores and learners' test performance is provided in Table 7.1 to explore possible correlations. The teachers personal PCK per key idea is an average of their scores obtained in each component of PCK. The performance of the learners per key idea is an average of their overall scores obtained in the test questions that explored aspects of the key idea. Table 7.1 also displays the Pearson's correlation coefficients and p-values for correlations between the teachers' personal PCK and the learners' performances per key idea. The data points consisted of individual learner's scores, each paired with his or her teachers' PCK score per key idea. The allocated PCK scores were correlated with the performance scores of all the learners for each of the three key ideas. According to Schober, Boer, and Schwarte (2018), indicators of the strength of the correlations are as follows; negligible (0.00 to 0.09), weak (0.10 to 0.39), moderate (0.40 to 0.69), strong (0.70 to 0.89) and very strong (0.90 to 1.00). As shown in Table 7.1, there were weak and insignificant correlations in the first and the second key idea while a moderate (r = 0.47) and significant ($p < 0.05$) correlation was found in the third key idea.

*Table 7.1: The relationship between teachers' personal PCK and learners' performance (n = 95).*

| Teacher identification | Electrostatic force PCK (1 - 4) | Electrostatic force Performance (%) | Electric field PCK (1 - 4) | Electric field Performance (%) | Electric field strength PCK (1 - 4) | Electric field strength Performance (%) |
|---|---|---|---|---|---|---|
| Ms VK | 2 | 61.0 | 2.4 | 60.9 | 2.8 | 45.3 |
| Mr JM | 3 | 49.8 | 2 | 59.1 | 1.8 | 32.8 |
| Ms SH | 2 | 26.5 | 2.2 | 42.5 | 1.6 | 13.4 |
| | r = 0.10, P > 0.05 | | r = 0.11, P > 0.05 | | r = 0.47, P < 0.05 | |

The information summarised in Table 7.1 is based on the three cases of the teachers who provided information from which their personal PCK could be inferred. As indicated earlier, no data for personal PCK is available for Mr PM because he did not return his CoRe tool and was also not available for an interview.

### 7.2.2 Teachers' enacted PCK and learners' outcomes

Similar to Table 7.1, Table 7.2 contains the average scores of the teachers' enacted PCK and learners' performances in each key idea. The table also includes the Pearson's coefficients for the correlations between the PCK and the performances. These correlations were calculated using 133 data points. As shown in Table 7.2, the correlation was moderate and significant in the first (r = 0.40, $p < 0.05$) and the third key idea (r = 0.44, $p < 0.05$) whereas it was weak and significant in the second idea (r = 0.30).

*Table 7.2: The relationship between teachers' enacted PCK and learners' performance (n = 133).*

| Teacher identification | Electrostatic force PCK score (1 - 4) | Electrostatic force Performance (%) | Electric field PCK score (1 - 4) | Electric field Performance (%) | Electric field strength PCK score (1 - 4) | Electric field strength Performance (%) |
|---|---|---|---|---|---|---|
| Ms VK | 2.4 | 61.9 | 2.2 | 60.9 | 3 | 45.3 |
| Mr JM | 2.4 | 49.8 | 2 | 59.1 | 2.5 | 32.8 |
| Ms SH | 2 | 26.5 | 1.2 | 42.5 | 1.25 | 13.4 |
| Mr PM | 2.8 | 57.1 | 1.6 | 52.1 | 2.25 | 36.3 |
| | r = 0.40, P < 0.05 | | r = 0.30, P <0.05 | | r = 0.44, P < 0.05 | |

The information summarised in Table 7.2 is based mainly on lesson observations in all four cases, supported by VSR interviews. However, Mr PM's PCK score was inferred from lesson observations only because he was not available for interviews, as explained in chapter three.

## 7.3 QUALITATIVE INVESTIGATION OF THE RELATIONSHIP BETWEEN TEACHERS' ENACTED PCK AND LEARNERS' OUTCOMES

In this section, qualitative evidence is presented to explore a relationship between teachers enacted PCK and learners' performance. The previous section has shown that teachers' enacted PCK, rather than their personal PCK, shows some correlation with learners' performance in all three key ideas. Therefore, the qualitative exploration of the relationship between teachers' PCK and learners' performance is focused on enacted, rather than personal PCK. The discussion is structured as follows: For each key idea, two cases are selected which illustrate correspondence and possible influence of the teachers' practice on learners' outcomes.

### 7.3.1 First key idea: Electrostatic force

With regard to the electrostatic force, the results of this study have shown a moderate positive correlation of 0.40. Furthermore, the correlation was statistically significant ($P < 0.05$).

Mr JM and PM's cases were chosen to illustrate the relationship between teachers' enacted PCK and learners' outcomes in terms of the electrostatic force. As shown in Table 7.2, Mr PM enacted richer PCK when teaching electrostatic forces compared to Mr JM. Similarly, his learners overall average performance was higher than that of Mr JM's learners. How the two teachers discussed Coulomb's law differed noticeably. Mr PM merely stated the law while Mr JM explained the relationships described by the law in detail using calculations that involved symbols and numbers. Seeing that the teachers differed in their engagement with the law, I examined the responses of their learners in the two multiple-choice questions that explored their understanding of the relationships. In the first question, learners were requested to select the option that contained the correct force of interaction after one of the charges was increased by a factor of four. The results revealed that Mr JM's learners performed better, which related to how they were taught. In the second question, it was the distance between the original charges that was doubled. In this regard, the performance of the learners in both classes was relatively similar and drastically lower than their average performance in the previous question. As such, this part of the learners' performance did not correlate well with the enacted PCK of the teachers. However, the performance in the first question suggests that Mr JM's decision to explain the relationships in detail benefited his learners.

I also observed that the two teachers solved problems using Coulomb's law following a similar approach, starting with the prior knowledge of charge interactions to obtain the directions of forces. They also emphasised drawing vector diagrams that were in proportion to the forces that they represented. Mr JM used an algebraic approach where he calculated the magnitudes of the forces before representing them with vector diagrams. In contrast, Mr PM drew the diagrams before calculating the magnitudes of the forces. Mr PM used qualitative and conceptual reasoning where he inferred the relative magnitudes of the forces by using the relationship between force and distance. As such, the force exerted by the charge closest to the reference charge was represented with a longer vector. It is evident that their diagrams revealed different ways of thinking. Mr JM's approach prevents a learning difficulty where learners assume that the closest charge exerts the strongest force regardless of its magnitude. Once the magnitudes of the forces were calculated, Mr PM specified their directions by writing it next to their magnitudes while Mr JM did not; instead, he described the nature of the interactions between the charges, i.e. attraction or repulsion.

To tests learners' ability to solve problems involving electrostatic forces, the diagram in Figure 7.2 was used.

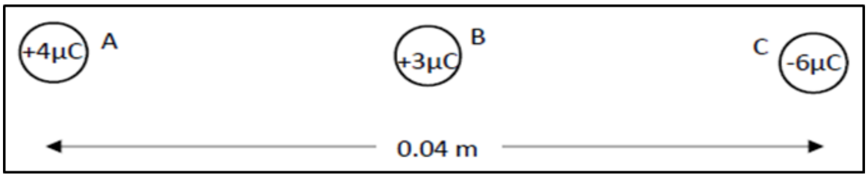



*Figure 7.1: One of the diagrams used to test learners' understanding of the electrostatic force.*

Learners were asked to determine the magnitudes and the directions of the forces exerted by sphere A and C on sphere B in Question 2.1.2 and 2.1.4. The results showed that Mr PM's learners performed remarkably better across the two questions (See Table 6.3). It was evident that the majority of the learners in each group indicated the directions of the forces similar to the way they were taught; with Mr JM's learners using charge interactions (see Figure 7.2).

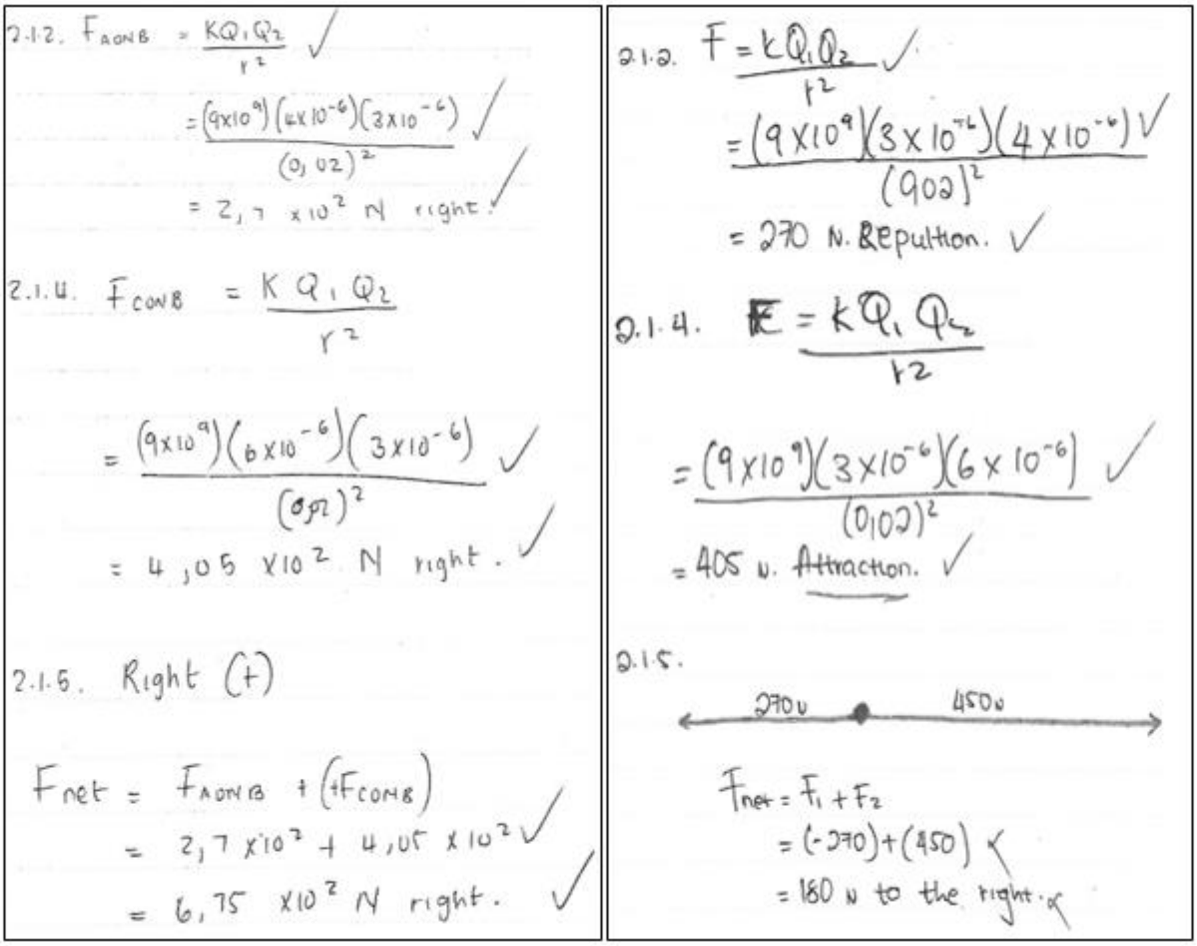



*Figure 7.2: The answers of some of the learners that were taught by Mr PM (left) and Mr JM (right).*

As indicated earlier, learners were awarded marks if the interactions were correct. Mr PM's learners also performed remarkably better when they were requested to determine the magnitude and the direction of the resultant force in Question 2.1.5 (See Table 6.3). Because the majority of Mr PM's learners specified the directions of the separate forces using left and right, it was easier for them to realise that the two forces were in the same direction. However, the majority of Mr JM's learners did not. Instead, they subtracted the two forces, which means that they possibly associated an attraction and repulsion with opposite directions. It is thus reasonable to conclude that Mr PM's decision to specify the directions of the forces in writing encouraged a deeper understanding of the superposition of forces in comparison to Mr JM.

The observations have also shown that how the two teachers discussed the application of Newton's third law in this topic was different. Mr PM emphasised the fact that each pair of charges exerted equal but opposite forces on each other in several instances, while Mr JM mentioned it once, after being interrupted by his mentor teacher. In this regard, the mentor teacher interfered in the lesson probably because she realised that Mr JM did not show any intentions to discuss the relevance of the law. The diagram in Figure 7.1 was used in the test to assess learners' understanding of the law. After having calculated the force exerted by sphere A on B, learners were requested to write down the magnitude and the direction of the force exerted by sphere B on A. In this particular question, Mr PM's learners performed remarkably better, matching the enacted PCK of their teacher because they specified the direction of the force exerted by sphere B on A. Some of Mr JM's learners revealed an understanding of the law because they wrote down the same magnitude that they had found in the preceding question. However, they indicated direction using charge interactions, which made it unclear whether they understood that the forces were in opposite directions. As such, they were not awarded the mark allocated for the direction.

These qualitative examples, therefore, illustrate how the learners that were taught by the teachers with a better PCK score, Mr PM, performed better in this key idea compared to Mr JM's learners.

### 7.3.2 Second key idea: Electric field

Concerning the electric field, the results of this study have shown a moderate positive correlation of 0.30. Nevertheless, the correlation was statistically significant ($P < 0.05$).

Mr JM and Ms SH's cases were chosen to illustrate the correlation between teachers' enacted PCK and learners' outcomes in terms of the electric field. How the two teachers discussed the concept of an electric field was considerably different. It was observed that Mr JM explained the direction of the electric field using a positive test charge while Ms SH provided the direction as it is stated in the textbook without explaining how it came about. In actual fact, she avoided the concept of a positive test charge altogether in her lessons. In the performance test, learners' understanding of the electric field was explored. The participating learners were requested to indicate the direction of the electric field at point B by using the diagram in Figure 7.3.

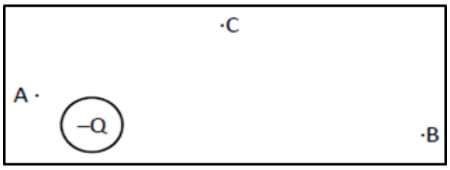



*Figure 7.3: One of the diagrams used to test learners' understanding of the electric field.*

The results indicated that Mr JM’s learners performed much better, with many of them indicating that the direction of the electric field is to the left at point B (See Table 6.4). Many of Ms SH’s learners provided incorrect answers, with some of them indicating that the electric field is downwards at point B. The results suggest that Mr JM’s explanation of the direction of the electric field using a positive test charge developed conceptual understanding. Despite their different approaches of discussing the direction of the electric field, it was observed that both teachers drew electric field patterns correctly. They also mentioned properties of electric field lines, particularly the fact that they should never touch or cross. However, it was Mr JM, who extended this discussion by explaining the reason why electric field lines do not touch. Similarly, his learners performed much better than Ms SH’s learners in the question that required them to draw electric field patterns for a pair of equal but opposite charges using the diagram in Figure 7.3. The results showed that many of Ms SH’s learners made errors in their drawings. The errors included drawings field lines between the charges but not on the outside, field lines that touch and drawing the curvature of the field lines incorrectly. It is thus reasonable to conclude that explaining how the directions of the electric field is obtained and why field lines do not cross benefitted many of Mr JM’s learners.

These examples illustrate how Mr JM’s learners showed more insight into electric fields than Ms SH’s learners, demonstrating that better learner performance was obtained for the teacher with a higher PCK score.

### 7.3.3 Third key idea: Electric field strength

With regard to the electric field strength, the results of this study have shown a moderate positive correlation of 0.44. Furthermore, the correlation was statistically significant ($P < 0.05$).

In terms of the electric field strength, Ms VK and Mr PM’s cases were chosen to illustrate the relationship between teachers’ enacted PCK and learners’ outcomes. The lesson presentations of the teachers revealed similar and different aspects in their enacted PCK. It was observed that Ms VK derived the formula $= k\,\frac{Q}{r^2}$ , while Mr PM did not; instead, he provided it without explaining how it came about. While deriving the formula, Ms VK made remarks that were suitable to prevent potential challenges. She mentioned that the test charge does not interfere with the electric field of the source charge, regardless of where it is placed. She also explained the roles and the use of the source and the test charge when calculating the magnitude of the electric field at a point which shows that she promoted conceptual understanding. Mr PM, on the other hand, was concerned that learners might confuse the formula $E = k\,\frac{Q}{r^2}$ with Coulomb's law. He also instructed them not to substitute signs of charges into the formula. One of the test items was carefully formulated to explore learners' understanding of the roles of the source and the test charge using the diagram in Figure 7.3 in the previous section. The learners were requested to determine the magnitude of the electric field at point B given the magnitude of the test charge, the force that it experienced at that point and its distance from the source charge. The magnitude of the source charge was not given. The results indicated that many of Mr PM's learners confused the roles of charges as they substituted Q in $E = k\,\frac{Q}{r^2}$ with the magnitude of the test charge. Although some of Ms VK's learners revealed the same misunderstanding, they were not as many as Mr PM's learners. Thus her decision to explain the roles of charges helped some of her learners determine the magnitude of the electric field at point B.

How the two teachers solved problems involving the electric field strength revealed similarities and differences. To determine the direction of the electric field at a point, both teachers instructed learners to imagine a positive test charge placed at the point of interest. They then instructed learners to study its interaction with the source charge to determine the direction of the force as it is the same as the direction of the electric field at that point. Ms VK also used another strategy to encourage effective learning. She drew the electric field pattern for the source charge and instructed learners to focus on the field line that passes through the point of interest as it indicates the direction of the electric field at that point. Once the directions of the fields were obtained, both teachers represented them using vector diagrams with suitable labels, e.g. $E_X$ at P. Ms VK drew vectors of equal lengths while Mr PM constructed them relative to their anticipated magnitudes according to the relationship between the electric field strength and distance from the source charge. Furthermore, both teachers specified the directions of the fields in writing in terms of a frame of reference to determine their resultants. The diagram in Figure 7.4 was used to test learners' ability to solve problems. Learners were required to determine the magnitude and the direction of the electric field strength set up by each source charge at point X. The learners were also requested to superimpose the fields to obtain their resultant in terms of magnitude and direction.

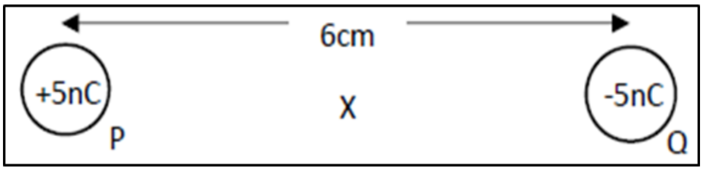



*Figure 7.4: One of the diagrams used to test learners' understanding of the electric field strength.*

With regard to determining the fields of the two charges, the results revealed that Ms VK's learners performed noticeably better. Careful analysis revealed that many of Mr PM's learners believed that the electric fields of the two source charges are in opposite directions at point X, seemingly because they have opposite polarities, a well-known difficulty reported by Li and Singh (2017). This was seldom the case among Ms VK's learners, suggesting that her use of two strategies to obtain the direction of the electric field at a point was more fruitful than Mr PM's single strategy.

These examples illustrate how Ms VK's learners showed more insight into an electric field strength than Mr PM's learners, demonstrating that better learner performance was obtained for the teacher with a higher PCK score.

### 7.3.4 Comparing the correlations across the key ideas

As reported in Section 7.2, the results of the study indicated moderate correlations between teachers' enacted PCK and their learners' outcomes in the first and the third key idea. It was in the second key idea where the correlation was weak. The question that arises is why the second key idea was an exception, although it was not the aim of the study to investigate factors that contribute to the strengths of the correlations. However, differences between the curriculum demands and the standard of learners' assessment came across as one such factor. In this study, teachers' PCK was examined using a rubric designed to reflect the demands of the curriculum while the test questions, on the other hand, were set similar to those used in national examinations. According to the curriculum and thus the PCK rubric, teachers are expected to thoroughly explain the concepts of the electrostatic force, electric field and electric field strength. In terms of the electric field, teachers are expected to describe the electric field and the fact that it is represented by imaginary field lines. Furthermore, they are expected to explain the direction of the electric field using a positive test charge. In addition, they have to discuss the density of electric field lines in relation to the electric field strength at a point, building towards the third key idea. In terms of PCK, the curriculum imposes several requirements; teachers were expected to present the concepts in a manner that promotes effective learning without inducing misunderstandings. For example, it is important to ensure that learners do not regard electric field lines as the means of transmission of electrostatic forces between charges (Pocovi & Finley, 2002). In terms of the electric field strength, the curriculum demands teachers to define the electric field strength as a force per unit charge. Furthermore, they are expected to deduce the formula $E = k\,\frac{Q}{r^2}$ by combining Coulomb's law and the definition of an electric field. In addition, the teachers are expected to help learners solve problems by determining magnitudes and the directions of electric field strengths at a point and to superimpose them to find their resultants.

On the other hand, the assessment of learners' performance in this study was based on typical national examination questions. The test items used in the first and the third key idea requested learners to apply knowledge to solve problems. For example, learners were expected to determine the magnitudes and directions of electrostatic forces acting on a reference charge and to superimpose them to find their resultant. However, for the second key idea, the test questions also included learners' ability to recall knowledge, for example describing an electric field and drawing patterns for unlike charges. It is, therefore, reasonable to tie the weak correlation between teachers' PCK and learners' outcomes in the second key idea to the mismatch between the curriculum demands and the questions used to test the key idea.

## 7.4 COMPARING PERSONAL AND ENACTED PCK IN RELATION TO LEARNER OUTCOMES

As indicated in Section 7.2, the results show that the outcomes of the learners correlated better with enacted PCK in comparison to the personal PCK. Because of this finding, I analysed the data further to explore the possible cause(s) of this difference in the correlations.

*Table 7.3: A summary of teachers' personal and enacted PCK scores.*

| Teacher | Electrostatic force | | | Electric field | | | Electric field strength | | |
|---|---|---|---|---|---|---|---|---|---|
| | Personal PCK (1 - 4) | Enacted PCK (1 - 4) | Performance (%) | Personal PCK (1 - 4) | Enacted PCK (1 - 4) | Performance (%) | Personal PCK (1 - 4) | Enacted PCK (1 - 4) | Performance (%) |
| Ms VK | 2 | 2.4 | 61.0 | 2.4 | 2.2 | 60.9 | 2.8 | 3 | 45.3 |
| Mr JM | 3 | 2.4 | 49.8 | 2 | 2 | 59.1 | 1.8 | 2.5 | 32.8 |
| Ms SH | 2 | 2 | 26.5 | 2.2 | 1.2 | 42.5 | 1.6 | 1.25 | 13.4 |
| Mr PM | – | 2.8 | 57.1 | – | 1.6 | 52.1 | – | 2.25 | 36.3 |

As shown in Table 7.3, the quality of the personal and the enacted PCK of the teachers was not necessarily the same, confirming results that have been reported in an earlier study (Mazibe et al., 2020). Based on this finding, I carefully selected examples that could illustrate how the variation between teachers' personal and enacted PCK could account for the differences in their correlations with learners' outcomes.

### 7.4.1 First key idea: Electrostatic force

In terms of the electrostatic force, I selected Ms VK and Mr JM's cases. As shown in Table 7.3, the quality of their personal PCK varied noticeably whereas that of the enacted PCK did not. However, there were similarities in their personal PCK despite the difference in the overall quality of their PCK. For example, some of the difficulties that they reported were similar. They mentioned that learners tend to substitute signs of charges into Coulomb's law which they confuse with vector characteristics. Mr JM also reported another major difficulty, mentioning that learners believe that in a set of three charges, it is the charge that is closest to the reference charge that exerts the strongest force regardless of his magnitude. What separated the teachers the most was their knowledge of representations used to support the teaching of electrostatic forces. It was evident that Mr JM was aware of powerful representations that demonstrate Coulomb's law in greater detail; varying the charge and distance between a ruler and pieces of paper, and varying the magnitudes of charges on an electric field hockey game. The representations mentioned by Ms VK were misplaced. For example, she mentioned that letting a pencil roll down to a stop helps learners understand Newton's third law. Based on their overall personal PCK, Mr JM had the upper hand as reflected by his overall score of three (3), compared to Ms VK's average score of two (2).

During teaching, the teachers enacted some of the knowledge that they had reported. For example, they both addressed the difficulty associated with the substitutions of signs into Coulomb's law, with Mr JM addressing it adequately. Furthermore, they both obtained the directions of the electrostatic forces from the prior knowledge of charge interactions. They differed in their use of representations, with Ms VK utilising them slightly better. For example, she labelled the forces more clearly, specifying the charge that exerted the force on the reference charge, while Mr JM used $F_1$ and $F_2$. In comparison to their reported knowledge of representations, both teachers did not enact all ideas that they reported. For example, it was observed that Mr JM did not demonstrate Coulomb's law while Ms VK did not attempt to "roll a pencil" to demonstrate Newton's third law. It was also observed that both teachers did not specify the directions of the forces; instead, they described charge interactions. This approach saw Ms VK making a mistake that forced her to revise her teaching strategy and specify the directions of the forces. This made it easier for her to determine the resultant forces in terms of magnitude and direction in a straight line. It is thus evident that the teachers did not vary noticeably in their enactment of knowledge. In fact, Mrs VK scored slightly better at 2.4, while JM's score dropped to 2.4, not matching his high score for personal PCK. Looking at the performance in the test items revealed that Ms VK's learners had the upper hand. Although Mr JM reported rich knowledge, the fact that he did not enact it disadvantaged his learners. As for Ms VK, the fact that she enacted a slightly richer PCK benefitted her learners.

### 7.4.2 Second key idea: Electric field

In terms of the electric field, I selected Ms VK and SH's cases. As shown in Table 7.3, the teachers' reported knowledge did not vary noticeably, whereas their enacted PCK did.

The personal PCK of the teachers revealed many similarities. Both teachers recognised magnetic fields as one of the pre-concepts for electric fields while Ms VK also referred to gravitational fields. Furthermore, both teachers mentioned that they would use iron filings to demonstrate magnetic field patterns, which would help learners understand electric field patterns. Again, Ms VK also mentioned that she would drop objects to demonstrate the presence of a gravitational field, making the objects interact with the earth. However, she missed an opportunity to explain that a similar representation in terms of the electric field would be the interaction between a charged insulator, like a ruler and pieces of paper. It was Ms SH who referred to using a charged balloon and pieces of paper to demonstrate the presence of an electric field that is responsible for charge interactions. Nevertheless, both teachers also reported that they would use a diagram showing a source charge and a positive test charge to explain how the direction of the electric field is obtained. Furthermore, they also reported the same difficulty; that is, learners find it difficult to draw electric field patterns accurately. Ms VK elaborated on this difficulty, indicating that they often allocate wrong directions to the electric field lines and that they draw field lines that touch or cross. She also added that this challenge is caused by the fact that field lines are imaginary, which makes it difficult for learners to conceptualise them.

The teachers differed noticeably in their enactment of PCK, although there were some similarities. For example, both teachers reminded learners of magnetic fields and how they are demonstrated using iron filings. The manner in which both teachers explained new knowledge was completely different. Ms SH read concepts as they are stated in the textbook without pausing for clarifications of explanations. As such, she simply stated that the direction of the electric field around a positive and a negative point charge while Ms VK explained how the direction is obtained. She used a diagram showing a source and a positive test charge as well as the path taken by the positive test charge. She also used a PhET simulation to support her explanation. This representation enabled Ms VK to demonstrate how the directions of the electric field lines came about, which was not the case in Ms SH's class. Although the two teachers emphasised the properties of field lines to minimise errors in their drawings, it was Ms VK who addressed another difficulty reported in the literature. The challenge is that learners do not infer the relative strength of the electric field from the density of field lines. As such, she alerted them to the fact that field lines spread out with distance, thus indicating the weakening of their field strength. To emphasise her point, she used a PhET simulation to show learners that the vector showing the force acting on the sensor becomes smaller when the distance from the source charge increases. The observations have indicated that the quality of the teachers' enacted PCK dropped compared to their personal PCK. However, it decreased noticeably in Ms SH's case.

As such, her learners were disadvantaged because she did not enact her knowledge effectively while Ms VK did. It is thus not surprising that her learners performed poorly compared to Ms VK's pupils.

### 7.4.3 Third key idea: Electric field strength

In terms of the electric field strength, I selected Mr JM and Ms SH's case. As shown in Table 7.3, their personal PCK for the electric field strength did not differ considerably while the quality of their enacted PCK was noticeably different.

Although the scores of the personal PCK of the teachers did not vary significantly, the information that they provided was different. The personal PCK of both teachers was centralised around the definition of an electric field (E = F/q). Furthermore, the information that they provided revealed gaps in their knowledge of the content, which influenced their decisions. For example, Ms SH mentioned that she would use the formula $E = k\,\frac{Q}{r^2}$ to derive the definition of an electric field ($E = F/q$), not realising that the sequence is the other way around. Mr JM mentioned that he would explain that the magnitude of the electric field is inversely proportional to that of the test charge if the force remains the same. This is inappropriate as the test charge does not generate the electric field. Both teachers indicated that they would use representations in the form of drawings to support the discussions of these concepts. The difficulties that they reported were also related to those concepts. Mr JM mentioned that learners do not understand that the direction of the force acting on a (positive) test charge is the same as that of the electric field because they do not understand the behaviour of a test charge in an electric field. Ms SH, on the other hand mentioned that gaps in learners' mathematical knowledge make it difficult for them to understand the derivation process. It is thus clear that both teachers were restricted in their knowledge for teaching the concept of the electric field strength.

During teaching, Mr JM enacted PCK that was noticeably better than his reported knowledge, whereas this was the opposite in Ms SH's case. It was observed that Ms SH was limited in her teaching as she read concepts as they are stated in the textbook without pausing for explanations and clarifications. Even the derivation of the formula $E = k\,\frac{Q}{r^2}$ was copied from the textbook and was not supported by the use of a suitable diagram. It was Mr JM who drew a diagram showing a source charge and a positive test charge to support the derivation of the formula. Ms SH also repeated the calculations that were given as examples in the textbooks, and presented them in a manner that promoted algorithms instead of conceptual understanding. For example, she showed learners how to determine the unknown value by plugging the given information into the appropriate formula. Furthermore, the examples that she repeated were focused on isolated charges. As such, learners were denied the opportunity to learn about the superposition of two electric fields at a point of interest in a straight line. Mr JM, on the other hand, solved a variety of problems involving fields of isolated charges, and the superposition of electric fields at a point. He also obtained the directions of the electric fields set up by charges by drawing their electric field patterns and alerting learners to focus on the line that passes through the point of interest as it indicates the direction of the field at that point. What let him down is that he did not specify the directions of the fields in writing next to their magnitudes. Nevertheless, a suitable free body diagram was constructed and used alongside a suitable frame of reference to superimpose the fields to obtain their resultants in terms of magnitude and direction. It is thus evident that the teachers did not enact the same knowledge that they had reported. Because Mr JM enacted richer PCK, his learners benefitted whereas Ms SH's learners were disadvantaged by the poor PCK enacted by their teacher.

## 7.5 CHAPTER SUMMARY

In this chapter I related teachers' personal and enacted PCK with the performances of their learners in the key ideas. For enacted PCK, correlations were moderate in the first and the third key idea but weak in the second key idea. A qualitative analysis of the relationships was provided, by discussing how teachers presented concepts against the responses of the learners in the test. I have also provided a discussion of the comparison between teachers' personal and enacted PCK. This discussion was necessitated by the fact that the performance of the learners was better related to the enacted PCK than to the personal PCK. It was thus necessary to compare the two manifestations and explore how they may have influenced learning directly or indirectly. In the next chapter, I provide a discussion of the answers to the research questions that guided this study, as well as the conclusions drawn from the data.

# 8. CHAPTER EIGHT: CONCLUSIONS

## 8.1 INTRODUCTION

This chapter presents the final discussion of the findings of the study that are reported in the preceding chapters. The discussion provides answers to the research questions that guided this study as well as the conclusions drawn from the data. Furthermore, the chapter provides a discussion of the limitations of the study as well as recommendations for future research and practice.

## 8.2 OVERVIEW OF THE STUDY

As indicated in the preceding chapters, the study aimed to investigate the relationship between teachers' PCK and learners' outcomes in electrostatics. The topic of electrostatics was selected mainly because it has seldom been investigated in terms of PCK (Melo et al., 2017; Melo-Nino et al., 2017), particularly at the concept level. Furthermore, the topic of electrostatics includes three distinguishable concepts that present different challenges for learners (Dega et al., 2013). The concepts are electrostatic force, electric field and electric field strength. The study was guided by the following research questions:

***Primary research question***

- What is the relationship between teachers' PCK and learners' outcomes in specific concepts of electrostatics?

***Secondary research questions***

- How does personal PCK compare across specific concepts of electrostatics for selected teachers?
- How does enacted PCK compare across specific concepts of electrostatics for the selected teachers?
- How does the achievement of learning outcomes compare across specific concepts of electrostatics for participating learners?

The static and the dynamic nature of teachers' PCK, termed personal and enacted PCK, respectively, in this study were both related to the learners' outcomes. Data reflecting the participating teachers' personal PCK was collected using a CoRe tool and lesson planning forms. Data for the enacted PCK was collected using lesson observations and VSR interviews. Two rubrics were developed to assess and quantify the quality of the participating teachers' personal and the enacted competences in the components of PCK. The components were as follows; learners' prior knowledge, curricular saliency, what is difficult to teach, representations including analogies and conceptual teaching strategies. The scores allocated for the separate teachers in the components were then averaged to produce a single score that reflects their PCK about the electrostatic force, electric field and electric field strength. Data for learners' performance was collected using a test and was analysed using content analysis.

## 8.3 ANSWERING THE RESEARCH QUESTIONS

The discussions of the results will be structured according to the research questions that guided this study by describing the personal and the enacted PCK of the participating teachers as well as the outcomes of their learners.

### 8.3.1 First sub question: Participating teachers' personal PCK

Although the aim of this study was not to compare the teachers among themselves, I have noticed that their personal PCK was predominantly low. For the two pre-service teachers, one might tie the low levels of PCK to the lack of teaching experience (Kind, 2009a). However, a surprising finding is that the pre-service teachers outperformed the in-service teacher that returned a completed CoRe. In this regard, the in-service teacher's personal PCK was low because she provided little information in the CoRe tool while she did not provide any written planning for her lessons whereas the pre-service teachers provided detailed plans and CoRes.

The results of the present study have also shown that the quality of the personal PCK of the participating teachers varied across the key ideas of electrostatics. Furthermore, the variations were case dependent, with each teacher reporting better PCK for a different key idea of electrostatics. Ms VK reported her personal best PCK for the electric field strength whereas Mr JM and Ms SH reported better PCK for the electrostatic force and the electric field, respectively. The results also extend the existing body of knowledge in terms of PCK at the concept level. Teachers' personal PCK has been explored by focusing on specific concepts of particular topics including acids and bases (Alvarado, Garritz, & Mellado, 2015), amount of substance (Padilla et al., 2008), and electric fields (Melo-Nino et al., 2017). However, the scholars did not compare the quality of PCK across the concepts. Instead, Alvarado et al. (2015) aggregated the information collected from the participating teachers to develop canonical PCK for the topic of acids and bases in a CoRe tool. Melo-Nino et al. (2017), on the other hand, explored teachers' emotions concerning PCK by targeting specific concepts of electrostatics to track its development following an intervention. The contribution of the present study in this regard is showing that the quality of the participating teachers' personal PCK varied across the concepts of electrostatics.

### 8.3.2 Second sub-question: Participating teachers' enacted PCK

The results of the study show that the participating teachers enacted low levels of PCK. Again, for pre-service teachers one would argue that the low levels were due to a lack of teaching experience (Kind, 2009a). What is surprising is the fact that the pre-service teachers outscored the in-service teachers in many of the fundamental concepts. Although the aim was not to explore the factors that shape the PCK of the teachers, I have made some speculations that are supported by evidence. In the case of Ms SH, her enacted PCK for the electric field and the electric field strength was restricted by her lack of content knowledge, similar to a finding by Rollnick et al. (2008). Mr PM on the other hand was more focused on teaching learners how to respond to exam questions instead of promoting conceptual understanding of concepts whether they are examined or not. He left out some of the key aspects of the fundamental concepts and focused on those that are examinable. This is ofcourse a speculation because the teacher did not avail himself for an interview which was meant to explore the reasons behind his enacted PCK. It is also possible that the pre-service teachers enacted better PCK because their lessons were graded whereas there was no obvious incentive for the in-service teachers.

Similar to the personal PCK, the quality of enacted PCK of the participating teachers also varied across the key ideas of electrostatics. Furthermore, the variations were also case dependent. The following are the key ideas in which the participating teachers enacted their personal best PCK; electric field strength for Ms VK, electrostatic force and electric field strength for Mr JM, electrostatic force for Ms SH and Mr PM. Again the results of the present study extend the existing body of knowledge in terms of enacted PCK. In the PCK literature, some researchers have discussed their findings on enacted PCK in relation to specific concepts of acids and bases (Nilsson & Vikström, 2015) and electromagnetism (Coetzee et al., 2020) without necessarily making comparisons across the concepts. The contribution of this study is showing that the quality of the participating teachers' enacted PCK varied across concepts.

### 8.3.3 Third sub-question: The participating learners' outcomes

The test results revealed that the performance of the learners varied across the key ideas of electrostatics. The overall performances across the key ideas were as follows; 44.8% for the electrostatic force, 64.6% for the electric field and 34.2% for the electric field strength. The participating learners had a good understanding of the description and representation of an electric field, whereas they revealed a limited understanding of calculating it as a physical quantity. The results of this study are similar to findings that have been reported in the literature and diagnostic reports about the relative difficulties of the concept of an electrostatic force and electric field strength (Garza & Zavala, 2013). It is clear that the electrostatic force was less challenging for the participating learners compared to the concept of an electric field as a physical quantity.

### 8.3.4 Main question: The relationship between teachers' PCK and learners' outcomes

Relating the teachers' personal and enacted PCK with the outcomes of their learners revealed contrasting findings. In terms of the enacted PCK, the results of this study revealed moderate correlations with learners' outcomes in the first and the third key idea. A weak correlation was found in the second key idea. These results support earlier findings reported in the literature about the positive correlation between the PCK that is enacted during practice and learners' outcomes (Alonzo et al., 2012; Walter, 2013). The results showed negligible correlations between the personal PCK and the outcomes of the learners for two of the three key ideas. It was only the key idea of the electric field strength that showed a moderate positive correlation between teachers' personal PCK and learners' outcomes. As indicated earlier, several studies have found substantial correlations between teachers' personal PCK and learners' outcomes (Hill et al., 2005; Kanter & Konstantopoulos, 2010). In the present study, a similar finding only emerged in one of the three concepts within the topic of electrostatics.

## 8.4 DISCUSSION OF THE RESULTS

As indicated earlier, the personal and the enacted PCK of the teachers as well as the performances of their learners varied across the key ideas. Although the aim of the study was not to investigate the causes of the variations, I have made speculations. In terms of PCK, I speculate that the variations may have been caused by the nature of the concepts, the teachers' depth of content knowledge about each concept and the "apprenticeship of observation" (Grossman, 1991). The apprenticeship of observation refers to preconceptions of teaching practice obtained from years of observing teachers in action. In several instances, the participating teachers revealed a lack of content knowledge which corresponded with inadequate PCK in some aspects of the concepts. For example, in terms of the personal PCK, Ms VK selected an irrelevant representation for demonstrating Newton's third law because she seemingly did not understand the law very well. Mr JM, on the other hand, reported that he would teach learners that the electric field at a point varies with changes in the magnitude of the test charge from the formula $E = F/q$. It was thus inevitable that his overall strategy promoted algorithms rather than conceptual understanding. With regard to enacted PCK, Ms VK omitted the directions of the resultant electrostatic forces in 2D and confessed during the interview that it was due to a lack of content knowledge. As such, her knowledge of curricular saliency was weak because learners were denied an opportunity to learn about resultant electrostatic forces in 2D. Furthermore, she and Ms SH seemed to lack a concrete conceptual understanding of the difference between an electric and a magnetic field. In these particular instances, it was evident that the lack of content knowledge impacted various components of PCK, for example, the teaching strategies that Mr JM suggested in his personal PCK. It is commonly understood within the PCK community that content knowledge is a pre-requisite for PCK (Kind, 2009a; Mavhunga, 2014). What the findings of this study show, however, is the possibility that different levels of content knowledge across key ideas may result in different PCK levels in the key ideas.

In terms of learners' outcomes, I propose that the variations in their performance levels across the key ideas were caused by the nature of the concepts. The concept of the electrostatic force is less abstract and more tangible than the concept of a field because it can be represented with ease using objects that attract and repel. Furthermore, the fact that forces are discussed in other topics makes it easier for learners to understand them in terms of charge interactions. The electric field, on the other hand, is a more abstract concept that is difficult to conceptualise (Senthilkumar et al., 2014), one which learners are hardly exposed to in preceding topics.

Before relating the personal and the enacted PCK of the teachers to the performances of their learners, I investigated the comparison between them. This activity revealed that the personal PCK of the teachers was not necessarily a reflection of the PCK that they went on to enact during teaching. This is a finding that has been reported earlier by Mazibe et al. (2020). In the present study, the teachers' personal PCK was better than their enacted PCK in some of the concepts whereas in others, it was the opposite. Furthermore, there was instances where the quality of the PCK remained the same in its static and dynamic forms. I again did not investigate the causes of the variations in the two manifestations of PCK. However, speculations about variations between personal and enacted PCK are made in the literature. In particular, researchers speculate that amplifiers and filters, for example beliefs and goals for teaching (Gess-Newsome, 2015) dictate the knowledge exchange from static to dynamic during teaching (Carlson & Daehler, 2019). For this study, and in particular the cases of the pre-service teachers, the variations may also have be attributed to the three month period between the completion of the CoRes and the lesson observations. It is possible that what the pre-service teachers learnt or realised within the three month period may have influenced their enactment of PCK.

The results have also made it clear that the performance of the learners was better related to the enacted PCK of the teachers than it was to the personal PCK. This finding is not surprising, considering the distance between personal PCK and learners as shown in the consensus model (Gess-Newsome, 2015) and the RCM of PCK (Carlson & Daehler, 2019). As shown in the models, it is only when the personal PCK is enacted in practice where it can have an impact on learning. This was hardly the case for the teachers as they enacted PCK that was predominantly different from their personal knowledge. Thus, learners were only able to access the PCK that was enacted in practice, which explains why it was better related to their performance.

## 8.5 CONCLUDING REMARKS

The results of this study have shown that the quality of the participating teachers' personal and the enacted PCK varied across the key concepts of electrostatics. These results extend the existing body of knowledge by providing empirical evidence that supports the notion that PCK has a concept specific nature (Carlson & Daehler, 2015; Smith & Banilower, 2015). Therefore, the study concludes that it is appropriate to consider PCK at the concept specific grainsize.

In terms of the relationship between teachers' PCK and learners' outcomes, the results revealed that it is the enacted PCK that correlated better with learners' outcomes compared to the personal PCK. The results also extend the existing body of knowledge by providing empirical evidence that supports the notion that while personal PCK is crucial as it informs lesson planning (Alonzo & Kim, 2016; Chantaranima & Yuenyong, 2014), the enactment of the knowledge is important given its direct impact on learning.

## 8.6 LIMITATIONS AND RECOMMENDATIONS

Although the findings of the study are meaningful, I recommend that they should be considered with caution, given the limitations of this research. The first limitation is the fact that a small sample of teachers was selected to provide an in-depth analysis of data (Maree, 2010). While the sample provided depth in terms of qualitative analysis, the quantitative analysis was limited. Secondly, the comparison of the personal and the enacted PCK was based on data that was collected three months apart in the case of pre-service teachers. In terms of the in-service teacher the returned a completed CoRe tool, the data for her personal PCK was not thorough. This has implications on the comparisons made. Thirdly, there is a possibility that the learners that were taught by pre-service teachers may have chosen not to engage with the content thoroughly because of the capacity of the pre-service teachers in their classes. Fourthly, the socio-economic statuses of the groups of learners that participated in the study were not the same. One group attended an adequately resourced school, whereas the others went to schools that had limited facilities. It would have been ideal to invite groups that are almost identical to participate in this study. However, the participation of the learners was determined by the availability of their teachers. Although I predominantly tied the outcomes of the learners to the PCK of their teachers with sufficient evidence, I acknowledge that other factors, for example socio-economic status, may have influenced the outcomes (Howie & Scherman, 2008). This is inline with the non-experimental research design that I have selected for this study. As I have stated in chapter three, the design does not allow the manipulation of variables. Therefore, a relationship between two variables may not necessarily indicate a cause an effect (Johnson & Christensen, 2012).

Despite the limitations of the study, several recommendations for research and practice are made from the findings. In terms of practice, the fact that enacted PCK correlated with learners' outcomes better than personal PCK highlights the importance of making teaching practice the centre of pre-service teacher training. Other researchers (e.g. Grossman et al., 2009) have also made this recommendation. In terms of research, I recommend a similar study that uses an experimental research design instead of the non-experimental research design used in this study due to the context in which it was conducted. The study would address the biggest limitation of the current study which was the inability to manipulate variables and tie the performance of the learners to the PCK of their teachers (Johnson & Christensen, 2012). The the recommended study would thus manipulate variables, i.e. let learners write similar tests before and after the lesson on the chosen topic so that the learners' performance gains are tied to the PCK of teachers with a greater degree of confidence. In terms of PCK, I recommend a study that develops a model that describes PCK at the concept specific grainsize, particularly the component of curricular saliency. Furthermore, it is necessary to conduct studies that investigate the causes of variations in the quality of PCK across the key ideas. Such studies would reveal teachers' strengths and weaknesses within particular concepts making up a topic. As such, pre-service teacher education and in-service teacher professional development may be tailored in such a way that addresses the concepts that require intervention.

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# 10. Appendices

## Appendix i: Completed CoRe tool – Expert CoRe

**Question 1: What do you intend learners to know about this idea?**

| |
|---|
| 1.1 The force of interaction between two charged objects, and its relation to the magnitudes of, and the distance between the centres of the charges. |
| • Coulomb's law:<br>- The force of interaction between two charges is directly proportional to the product of the magnitudes of the charges.<br>- The force is also inversely proportional to the square of the distance between the centres of the charges.<br>• The direction of the electrostatic force exerted by one charge on another.<br>- Like charges repel and push each other away.<br>- Unlike charges attract and pull each other.<br>• The application of Newton's third law:<br>- Interacting charges exert equal but opposite forces on each other regardless of their sizes.<br>• The application of Coulomb's law to determine the magnitude of the electrostatic force between two charges.<br>- Signs of charges must not be included when substituting into Coulomb's law.<br>• The magnitude and the direction of the resultant electrostatic force on a reference charge in a set of three charges in straight line and in 2D.<br>- In a straight line: select a frame of reference and add the two forces accordingly.<br>- In 2D: the theorem of Pythagoras is used to obtain the magnitude of the resultant force while trigonometric ratios are used to obtain the direction of the force in terms of an angle. |
| 2.1 The representation of an electric field around a charged object. |
| • The description of an electric field:<br>- The region of space around a source charge where another charge or a polarised object experiences an electrostatic force.<br>• The representation of a field using electric field lines.<br>- The direction of the electric field of a source charge at any point is the direction of the force exerted by the source charge on a positive test charge placed at that point.<br>• The interpretation of electric field lines:<br>- Electric field lines point away from a positive charge and towards a negative charge.<br>- The density of electric field lines represents the strength of the electric field. Since the density of the field lines around a point charge decreases with distance, so does the electric field strength. |
| 2.2 The electric field as a physical quantity. |
| • The definition of an electric field:<br>- The electric field at a point is defined as the electrostatic force per unit charge placed at that point: $\vec{E} = \frac{\vec{F}}{q}$<br>• The magnitude of the electric field set up by a single charge at a point:<br>- The magnitude of the electric field at a point can be determined using the definition of an electric field; $\vec{E} = \frac{\vec{F}}{q}$ or the formula $\vec{E} = k\frac{Q}{r^2}$. An electric field is a vector quantity measured in $N.C^{-1}$.<br>• The superposition of two electric fields at a point:<br>- Grade 11 learners are limited to the superposition of two electric fields at any point that is in line with the two source charges. |

**Question 2: Why is it important to know this idea? Refer to the relation of this idea to other topics in CAPS.**

| |
|---|
| 1.1 The force of interaction between two charged objects, and its relation to the magnitudes of, and the distance between the centres of the charges. |
| • Coulomb's law can be used to help learners understand that changing the magnitude of the test charge 'q' in the definition of an electric field ($E = \frac{F}{q}$) does not affect the magnitude of the electric field. Any change on the magnitude of 'q' results in the same in the magnitude of 'F' thus 'E' remains unchanged.<br>• Coulomb's law is necessary when deriving the formula $\vec{E} = k\frac{Q}{r^2}$ which is used to obtain the electric field of a charge at a point. |
| 2.1 The representation of an electric field around a charged object. |
| • The electric field is the mechanism by which charged and polarised objects interact without making contact.<br>• The direction of the electric field of a point charge at any location is necessary when solving problems that involve field superposition.<br>• The density of field lines reflects the strength of the electric field. This concept can be linked with the relationship between the strength of the electric field and distance in the next key idea represented by the formula $E = k\ \frac{Q}{r^2}$. |
| 2.2 The electric field as a physical quantity. |
| - The electric field of a point charge 'E' is analogous to the gravitational acceleration 'g' of a body of mass:<br>  - Since $F = mg = G\frac{Mm}{r^2}$. It follows that $g = G\frac{M}{r^2}$. This acceleration is always towards the body of mass.<br>  - Similarly $F = qE = k\ \frac{Qq}{r^2}$. Thus it follows that $\vec{E} = k\frac{Q}{r^2}$. Different from the acceleration is the fact that the electric field is away from a positive point charge while it is towards a negative one. |

**Question 3: What else do you know about this idea that you do not intend learners to know yet?**

| |
|---|
| 1.1 The force of interaction between two charged objects, and its relation to the magnitudes of, and the distance between the centres of the charges. |
| • The concept of an electric field which is the mechanism by which charged objects exert electrostatic forces on each other without making contact. This concept will be addressed in the next two key ideas. |
| 2.1 The representation of an electric field around a charged object. |
| • The fact that the strength of an electric field can be quantified. This concept is reserved for the third key idea. |
| 2.2 The electric field as a physical quantity. |
| • Electric fields for other charged objects other than point charges, for example parallel plates:<br>  - The electric field between parallel plates depends on the potential difference and the distance between the plates: $\mathrm{E} = \frac{\mathrm{V}}{\mathrm{d}}$. Thus the electric field is also measured in a volt per metre ($V.m^{-1}$). |

**Question 4: What are the necessary pre-concepts that learners must have before teaching this idea? What are the common learners' misconceptions about the pre-concepts?**

| |
|---|
| 1.1 The force of interaction between two charged objects, and its relation to the magnitudes of, and the distance between the centres of the charges. |
| • Newton's law of universal gravitation:<br>- The law of universal gravitation is related to Coulomb's law. The only difference is that it refers to the attraction between bodies of mass while Coulomb's law describes the attraction and repulsion between charges.<br>- Some learners interpret the inverse square law incorrectly. They believe that if the distance between charged objects halves, the force between them doubles.<br>• The nature of interaction between charged particles:<br>- This prior knowledge is used to determine the directions of the forces acting on a reference charge.<br>• Newton's third law:<br>- This law is applicable in this key idea because two interacting charges exert equal but opposite forces on each other regardless of their magnitudes and polarity.<br>- Learners tend to think that bigger objects exert stronger forces on smaller ones (Hestenes, Wells & Swackhamer, 1992).<br>• Mechanics concepts:<br>- A force is a vector quantity with magnitude and direction. It must thus be represented with a vector diagram to support problem solving strategies.<br>- A net force is a single force that represents all the forces acting on an object.<br>• Strategies used to obtain the magnitude and the direction of the force acting on the reference charge in a set of three in 2D:<br>- The theorem of Pythagoras yields the magnitude of the resultant force while trigonometric ratios are used to obtain its direction in terms of an angle. |
| 2.1 The representation of an electric field around a charged object. |
| • The concept of magnetic fields and their representations:<br>- This prior knowledge can be used to help learners understand that a field is a region where a force is experienced; magnetic fields are responsible for magnetic forces while electric fields are responsible for electrostatic forces.<br>- Magnetic field lines can help learners understand that electric fields are also represented with field lines and the shapes of the lines in an attraction and repulsion. Furthermore, the density of the field lines is higher near the poles and the charges where the respective fields are stronger.<br>- The challenge is that learners might think that the North and the South Pole represent positive and negative charges respectively (Saglaam & Miller, 2016).<br>• The nature of charge interactions:<br>- This prior knowledge is necessary when obtaining the direction of the electric field set up by a point charge using a positive test charge. |
| 2.2 The electric field as a physical quantity. |
| • This key idea requires an understanding of the first two key ideas: the electrostatic force as well as the description and the representation of an electric field using field lines.<br>• Given the vector nature of an electric field, learners must be able to add vectors to obtain their resultant. |

**Question 5: What do learners find difficult to understand about this idea and why?**

| |
|---|
| 1.1 The force of interaction between two charged objects, and its relation to the magnitudes of, and the distance between the centres of the charges. |
| • The inverse square law is challenging for some learners:<br>- They believe that when the distance between charged objects halves, the force between them doubles (Maloney et al., 2001).<br>- They also believe that the interaction ceases when the distance between charges increases because the objects don't physically appear to attract and repel anymore (Ajredini et al., 2013).<br>• Some learners associate the polarity of charges with vector characteristics (DoBE, 2016):<br>- They substitute signs of charges into Coulomb's law and translate them into vector characteristics.<br>- Substituting signs of unlike charges results in a negative force, which learners immediately associate with the negative direction.<br>• Some learners do not understand the application of Newton's third law:<br>- They think that bigger charges exert stronger forces on smaller charges (Ajredini et al., 2013; Bohigas & Periago, 2010; Maloney et al., 2001). |
| 2.1 The representation of an electric field around a charged object. |
| • Some learners think that electric fields only exist on the actual field lines and not in between them (Tornkvist et al., 1993).<br>• Some learners think that the electric field strength is constant along an electric field line instead of interpreting the density of the lines (Saarelainen et al., 2007; Tornkvist et al., 1993).<br>• Some learners draw electric field patterns incorrectly. Their field lines touch, cross and loop around the same charge while others have arrows pointing in opposite directions (Taskin & Yavas, 2019; Tornkvist et al., 1993). |
| 2.2 The electric field as a physical quantity. |
| • Some learners associate the electric field at a point with the charge (usually a test charge) placed at that point (Bohigas & Periago, 2010). They confuse the roles of the charges in the following formulae; $\vec{E} = \frac{\vec{F}}{q}$ and $\vec{E} = k\frac{Q}{r^2}$ (DoBE, 2014).<br>• Some learners misinterpret the relationships described by the definition of an electric field; $\vec{E} = \frac{\vec{F}}{q}$.<br>- They think that changing the magnitude of the test charge 'q' has an effect on the electric field 'E' at the same point.<br>• Some learners confuse the polarity of charges with vector characteristics (DoBE, 2016):<br>- They substitute signs of charges into the formula $\vec{E} = k\frac{Q}{r^2}$ and translate the signs into an indication of direction.<br>- Substituting a negative charge results in a negative electric field which learners associate with the negative direction.<br>• Some learners believe that the electric fields set up by like charges at any point always add up while those set up by unlike charges cancel each other out (Li & Singh, 2017). |

**Question 6: Which representations would you use to teach this idea and how? Also include the purposes served by the representations.**

**1.1** The force of interaction between two charged objects, and its relation to the magnitudes of, and the distance between the centres of the charges.

- Demonstrate the interaction between charged balloons:
  - Rub two balloons with the same cloth and place them closer to each other so that they repel. Vary the charges on the balloons by rubbing them slightly and vigorously.
  - The aim of this demonstration is to show learners that the repulsion of the balloons intensifies with the increase in charge. Thus the force is directly proportional to the magnitude of the charges.
  - In the second demonstration, rub the charges vigorously and vary the distance between them while learners observe.
  - The aim of this demonstration is to show that the repulsion intensifies with the decrease in distance. As such, the force is inversely proportional to the distance.
- Represent the forces acting on a reference charge using vector diagrams:
  - Use free body diagrams where a dot represents the reference charge.
  - In 2D problems, change the tail-to-tail configuration into a head-to-tail. The latter will help learners substitute the forces into the theorem of Pythagoras and to select the trigonometric ratio to obtain the direction of the resultant force.

**2.1** The representation of an electric field around a charged object.

Use demonstrations that reveal an interaction between two objects that are not necessarily in contact with each other. The following demonstrations are suggested:

- Rub a balloon with a cloth to charge it and let it (i) bend a soft stream of water, (ii) pick up a piece of paper, (iii) topple and drag an aluminium can and also let it (iv) repel another charged balloon.
- Van Der Graaf Generator:

(i) Place polystyrene balls in a glass jar placed on top of the charged metal sphere. The balls will start jumping around.

(ii) Hang a polystyrene ball using a string over the metal sphere. The string and the ball will be repelled.

(iii) Tape strings at various points around

- A Drawing showing a source and various positive test charges around it.
  - Draw vectors showing the directions of the forces exerted by the source charge on each of the positive test charges. The strings in the Van Der Graaf generator can be used to show learners the orientation of electric field lines at various locations around a charge.
- Demonstrate an electric field patterns using semolina seeds in oil:

(i) Pour oil into a petri dish and dip two electrodes in it.

(ii) Connect the positive electrode to an electrostatic generator, for example a Van Der Graaf generator.

(iii) Earth the other electrode.

(iv) Pour polarisable seeds (for example semolina seeds) and let learners observe

2.2 The electric field as a physical quantity.

- A drawing of an electric field patterns of a single point charge:
  - Place two positive test charges at two different locations. Location A must be closer to the point charge while location B is much further.
  - The aim of this drawing if to prompt learners to study the density of the field lines to indicate the location where the field is stronger, which is location A. Furthermore, the diagram can be used to prompt learners to indicate the test charge that experiences a stronger force due to the source charge, this will be the charge placed at A. This discussion can be used to define an electric field at a point as the force per unit of charge.
- A drawing of a source charge and a positive test charge.
  - Label the charges 'Q' and 'q' and indicate the distance 'r' between them.
  - This demonstration can be used to help learners understand that the force exerted on the test charge 'q' by the source charge 'Q' can be determined using the definition of an electric field at a point as well Coulomb's law. Substitute the variables accordingly into coulomb's law and derive the formula$E = k\,\frac{Q}{r^2}$.
- Drawings of electric field patterns:
  - Suppose you have a diagram showing two source charges and a point of interest in a straight line that passes through the charges. To obtain the direction of the electric field set up by each source charge at that point, draw a separate diagram showing the electric field pattern of the charge.
  - Place the point of interested preferably on a field line according to the arrangement of the charge and the point of interest. Erase the other field lines and leave the line that indicated the direction of the field.
- Drawings of electric field vectors:
  - After obtaining the directions of the fields, represent the fields using vector diagrams.
  - The aim of this representations is to help learners understand the calculation of the net electric field at a point.
  - It is also recommended to draw the complete electric field pattern for the interacting charges for learners to see that there are no field lines halfway between two identical charges while the field lines add up when the charges have opposite polarities.

**Question 7: Which conceptual strategies would you use to teach this idea and how? Include conceptual questions that you would ask in your teaching of this idea.**

1.1 The force of interaction between two charged objects, and its relation to the magnitudes of, and the distance between the centres of the charges.

- Demonstrate the relationships described by Coulomb's law using charged balloons as indicated earlier.
- Introduce Coulomb's law based on the demonstrations, that is, $F \propto Q_1Q_2$ and that $F \propto \frac{1}{r^2}$. Combine the relationship with the electrostatics constant to produce the following formula $F = k\,\frac{Q_1Q_2}{r^2}$.

| | |
|---|---|
| • | Explain the relationships described by Coulomb's law separately starting with the force and the product of the charges before moving on to the inverse square law.<br>- Give learners a diagram showing two charges exerting a force F on each other. Alter the magnitudes of the charges while the distance is kept the same and ask learners to indicate the factor by which the force changes.<br>- With regards to the inverse square law, alter the distance between the charges while their magnitudes are kept the same and ask learners to indicate the factor by which the force changes. |
| • | Explain the application of Newton's third law.<br>- Draw a diagram showing two unequal charges, for example $Q_A = Q$ and $Q_B = 2Q$:<br>- Ask learners to compare the magnitudes of the forces that the charges exert on each other. Some of them will indicate that the bigger charge exerts a stronger force.<br>- To address this challenge, specify the magnitudes of the charges (for example 2nC and 4nc) and the distance between them. Use the given values to calculate the forces that charge A exerts on charge B as well as the force exerted by charge B on charge A. This should help learners realise that the forces that the charges exert of each other is the same regardless of their magnitudes. |
| • | Solve problems using Coulomb's law:<br>- Instruct learners not to substitute signs of charges into Coulomb's law. Ask them to study the interactions of the charges and to indicate the directions of the forces exerted on the reference charge. Phrase questions as "…what is sphere A doing to sphere B? Where would sphere B move?"<br>- Represent the forces using vector diagrams after obtaining their directions from studying the interactions of the charges. In 2D, change the tail-to-tail configuration into a head-to-tail. This is to show learners how the forces fit into the theorem of Pythagoras and which trigonometric ratios to use to obtain direction in terms of an angle. |
| 2.1 | The presentation of an electric field around a charged object. |
| • | Use the demonstrations discussed under representations to prompt learners to think about the causes of the interactions between the objects used. You can phrase the question as follows: "How does one balloon push the other balloon without making contact with it?" |
| • | Refer learners to their prior knowledge of magnetism and prompt to think about the attraction and repulsion between poles of magnets. |
| • | Use the demonstrations to describe an electric field as the region of space around a charged object where another charged or polarised object experiences an electrostatic force. Relate this force with other non-contact forces: gravitational and magnetic forces. |
| • | Obtain the directions of electric fields set up by point charges by using a drawing of a diagram showing a source charge 'Q' and various positive test charges 'q' around it. |
| • | Ask learners to study the interactions between the charges and to indicate the direction of the force that each positive test charge experiences due to the source charge. Represent the forces with vector diagrams and emphasise that they indicate the direction of the electric field at that point. |
| • | Draw the electric field patterns for single point charges, a positive and a negative point charge, and use the patterns to prompt learners to interpret the density of the field lines. You can also use the interactions between the objects to engage with this concept. The electric field around a charged balloon weakens with distance, as such, it must be brought closer to the other balloon it order for a repulsion to be observable. |
| • | Draw electric field patterns for interacting charges where bigger charges must have more field lines than smaller ones. |
| 2.2 | The electric field as a physical quantity. |
| • | Draw an electric field for a single point charge to facilitate the development of new knowledge:<br>- Place two identical positive test charge at location A (closer to the point charge) and B (further away).<br>- Ask learners to indicate the location where the electric field is stronger by interpreting the density of the electric field lines. This should be location A.<br>- Ask them to indicate the charge that experiences the strongest force in their respective locations. This should be the charge placed at A.<br>- This discussion can help learners realise that a stronger electric field exerts a stronger force on a test charge. Use the discussions to define the electric field at a point as the force per unit charge at that specific point. |

- Ask learners to indicate what would happen to the electric field at a point if the magnitude of the test charge was either doubled or halved. Many of the will indicate that the electric field changes. Use Coulomb's law to address this challenge.

- Derive the formula $\vec{E} = k\frac{Q}{r^2}$ by using a diagram showing the source charge 'Q', the test charge 'q' and the distance 'r' between the charges:
  - Ask learners to formulate an expression that can be used to calculate the force exerted by the source charge on the test charge [$\mathrm{F} = \mathrm{k}\ \frac{\mathrm{Q\ x\ q}}{\mathrm{r}^2}$].
  - Combine the expression with the definition of an electric field to derive the formula $\mathrm{E} = \mathrm{k}\frac{\mathrm{Q}}{\mathrm{r}^2}$. This formula can be used to show learners that the magnitude of the electric field does not depend on the positive test charge. Instead it depends on the magnitude of the source charge and the distance of the point of interest.
  - Engage with the relationships described by the newly derived formula and relate them to the drawings of electric patterns in the second key idea.
  - Because the density of electric fields represent the strength of electric field, bigger charges must have more field lines around them because they set up stronger fields. Furthermore, the field lines spread out with distance where the field is weaker.
- Solve problems using the newly derived formula:
  - Draw the electric field pattern and focus on the field line that passes through the point of interest as it gives the direction of electric field at that point. Represent the electric field using a vector diagram. Repeat this explanation for the other charge. It is important to pretend as if the other charge is absent while drawing the electric field patterns to avoid curving field lines.
  - Emphasise the fact that signs of charges must not be substituted in the formula and that the direction of the electric field is determined by the polarity of the source charge.
  - Redraw the electric field vector diagrams after the electric fields have been calculated relative to the magnitudes to help learners conceptualise the resultant electric field before calculating it.
  - Place an electron at the point of interest and determine the electrostatic force acting on it after the resultant field at that point has been calculated. Emphasise the fact that the force on an electron is always in the opposite direction to that of the electric field.

## Appendix ii: Personal PCK rubric

| | Limited | Basic | Developing | Exemplary |
|---|---|---|---|---|
| Learners' prior knowledge | • The teacher did not refer to any relevant prior knowledge. | • The teacher mentioned a few major concepts as prior knowledge.<br>• The concepts are not discussed, thus possible difficulties and gaps are not specified. | • The teacher referred to some major concepts that serve as prior knowledge.<br>• The concepts are discussed adequately, however, gaps and difficulties are specific to one concept. | • The teacher mentioned most of the major concepts that serve as prior knowledge.<br>• The concepts were discussed extensively where possible difficulties and gaps have been specified. |
| Curricular saliency | • The teacher did not refer to new concepts prescribed in the curriculum.<br>• The teacher did not show links between prior knowledge and new concepts.<br>• There is no evidence of sequencing and explanation of the interrelatedness between concepts.<br>• There is no indication of the importance of the new concepts. | • The teacher referred to a few major concepts prescribed in the curriculum.<br>• Links between the new concepts and prior knowledge are implied.<br>• The sequencing and explanation of the interrelatedness between concepts is inadequate.<br>• The importance of concepts does not include scaffolding. Instead, it is for examination purposes. | • The teacher referred to most of the major concepts prescribed in the curriculum.<br>• Links between the new concepts and prior knowledge are predominantly implied.<br>• The sequencing and the interrelatedness of the concepts are adequately explained.<br>• The importance of concepts includes scaffolding, but the subsequent future concepts are not specified. | • The teacher reported all major concepts prescribed in the curriculum.<br>• The links between new concepts and prior knowledge are adequately explained.<br>• The sequencing of the concept is logical and the interrelatedness between concepts is clearly explained.<br>• The importance of concepts includes scaffolding into specific and relevant future concepts. |
| What is difficult to teach? | • The teacher did not report concepts that are difficult for learners.<br>• Gate keeping concepts for learners' difficulties are also absent. | • The teacher mentioned a few areas of learners' difficulties.<br>• The difficulties were not explained and clarified.<br>• Gate keeping concepts and reasons for the difficulties are either missing, minor or generic, e.g. "learners' mathematical knowledge is lacking". | • The teacher mentioned some of the areas of learners' difficulties.<br>• Some of the areas of difficulties are adequately explained and specified while others are not.<br>• The gate keeping concepts as well as the causes of difficulties are adequately explained, however, they are limited to the identified areas of difficulty. | • The teacher reported most of the areas of learners' difficulties.<br>• The difficulties are extensively explained and specified.<br>• The identified gate keeping concepts and causes of the difficulties are linked with learners' prior knowledge and misconceptions that hinder successful learning of the concepts. |

| | | | | |
|---|---|---|---|---|
| Representations including analogies | • Representations are not reported. | • The teacher identified a single representation.<br>• There is no indication of how the representation works.<br>• There is no indication of the concepts that are supported by the representation including conceptual change and development. | • The teacher mention one or more suitable representation.<br>• The teacher explained how the representations work.<br>• The representations are predominantly used for one purpose; to support conceptual change OR conceptual development. | • The teacher identified several suitable representations.<br>• The teacher explained how the representations work as well as the concepts that they support.<br>• The representations are used to support conceptual change as well as conceptual development. |
| Conceptual teaching strategies | • Teaching strategies are listed but not explained.<br>• There are no connections between the strategies and the key ideas. | • Teaching strategies are listed but only a few are explained.<br>• The strategies seldom refer to prior knowledge and ways of addressing possible difficulties.<br>• There is evidence of the development of few new concepts from corresponding prior knowledge.<br>• The strategies seldom refer to ways of uncovering learners' understanding, difficulties and addressing the difficulties.<br>• These strategies exclude the use of representations or the representations do not appear to be effective.<br>• There is no evidence of cognitive involvement of learners. | • Several teaching strategies are mentioned and adequately explained.<br>• The use of strategies that uncover prior knowledge and address gaps and difficulties are implied.<br>• There is evidence of the development of some of the new knowledge from corresponding prior knowledge.<br>• The use of strategies that uncover learners' understanding, difficulties and approaches of addressing the difficulties is implied.<br>• The strategies include representations that either support conceptual change or development.<br>• There is evidence of cognitive involvement of learners. | • Several teaching strategies are reported and extensively explained.<br>• The strategies uncover prior knowledge and adequately address potential gaps and difficulties.<br>• The strategies develop new concepts from corresponding prior knowledge.<br>• The strategies refer to learners' understanding and potential difficulties with approaches tailored to address them.<br>• The strategies include representations that serve various purposes; addressing difficulties in the prior knowledge, new concepts and supporting conceptual development of new knowledge.<br>• Learners are cognitively involved in activities. |

## Appendix iii: Enacted PCK rubric

| | Limited | Basic | Developing | Exemplary |
|---|---|---|---|---|
| Learners' prior knowledge | • No facilitation of discussions that uncover and address learners' prior knowledge. | • There are seldom discussions that uncover prior knowledge.<br>• The prior knowledge is provided by the teacher as standardised concepts.<br>• Most gaps and challenges in the prior knowledge are thus not exposed and addressed. | • The teacher facilitates rich discussions that uncover some of the relevant prior knowledge.<br>• The teacher acknowledges correct understanding and sufficiently addresses gaps and challenges. However, these are limited to some of the prior knowledge. | • The teacher facilitates rich discussions that uncover most of the prior knowledge.<br>• The teacher acknowledges correct understanding and adequately addresses gaps and challenges in the prior knowledge. |
| Curricular saliency | • The teacher does not discuss concepts that are prescribed in the curriculum.<br>• The new concepts are not developed from or linked with corresponding prior knowledge.<br>• The sequencing of concepts is illogical and the interrelatedness of the concepts is not explained. | • The teacher discusses only a few concepts prescribed in the curriculum.<br>• A few of the new concepts are developed from, or linked with corresponding prior knowledge.<br>• The sequencing of concepts is illogical and the interrelatedness of concepts is seldom explained. | • The teacher discusses most of the significant curriculum bound concepts.<br>• Most of the concepts are developed from, or linked with corresponding prior knowledge.<br>• The sequencing of concepts is logical and the interrelatedness of concepts is often explained. | • The teacher discusses all concepts prescribed in the curriculum.<br>• The new concepts are developed from, or linked with corresponding prior knowledge.<br>• The sequencing of concepts is logical and the interrelatedness of the concepts is explained. |
| What makes it difficult to teach this key idea? | • No facilitation of discussions that uncover learners' understanding of concepts and difficulties.<br>• The teacher makes no effort to help learners understand difficult concepts. | • Discussions that uncover learners' understanding of concepts and difficulties are seldom facilitated.<br>• Thus a few areas of learners' difficulties are addressed.<br>• The teacher's attempts to explain difficult concepts by providing standardised phrases, e.g. "the field line points away from a positive charge." | • The teacher facilitates cognitive discussions that uncover learners' understanding of concepts and difficulties.<br>• The teacher addresses difficulties without paying attention to the gate keeping concepts that hinder successful learning of new concepts. | • The teacher facilitates cognitive discussions that uncover learners' understanding of concepts and difficulties.<br>• The teacher addresses difficulties starting from gate keeping concepts that hinder successful learning of new concepts.<br>• The teacher confirms correct understanding afterwards. |

| | | | | |
|---|---|---|---|---|
| Representations including analogies | • Representations are not used to support the discussion of concepts. | • Representations are seldom used to support the discussion of concepts.<br>• Most of the concepts that require representations are discussed without utilising them.<br>• When used, the representations are poorly developed and mostly ineffective. | • Representations are often used to support the discussion of concepts.<br>• A few concepts that require representations are discussed without utilising them.<br>• The representations serve mainly one purpose; fostering conceptual change or conceptual development. | • Representations are used to support the discussions of concepts whenever necessary.<br>• The representations serve various purposes; conceptual change in development with regards to prior knowledge and new concepts. |
| Conceptual teaching strategies | • The teacher does not engage with prior knowledge to explore understanding, gaps and difficulties in it.<br>• The new concepts are not linked with or developed from corresponding prior knowledge.<br>• The sequencing of concepts is illogical and the interrelatedness of concepts are not explained.<br>• Representations are not used to engage with prior knowledge, areas of difficulties and new concepts. | • The teacher engages with prior knowledge by asking close ended questions and provided answers to the questions.<br>• Gaps and difficulties in the prior knowledge are thus not addressed.<br>• Links between new concepts and prior knowledge are either absent or inadequately explained.<br>• The teacher seldom facilitates discussions that expose learners' understanding and difficulties.<br>• The teacher ignores responses that are not in line with the expected answer and eventually provides the correct answer by stating standardised phrases.<br>• Representations are seldom or ineffectively used to engage with learners' prior knowledge, areas of difficulties and new concepts. | • The teacher facilitates discussions that prompt learners to reveal some of their prior knowledge.<br>• The teacher addresses some of the gaps and/or difficulties in the prior knowledge by creating conceptual conflict that informs conceptual change.<br>• Some of the new concepts are linked with or developed from corresponding prior knowledge.<br>• The teacher facilitates discussions that learners' understanding of some of the new concepts, difficulties and created conceptual conflicts that inform conceptual development.<br>• Representations are often used for a single purpose; inform conceptual change or development. | • The teacher facilitates discussions that prompt learners to reveal most of their prior knowledge.<br>• The teachers addresses difficulties in the prior knowledge by inducing conceptual conflicts that inform conceptual change.<br>• The new concepts are linked with or adequately developed from prior knowledge.<br>• The teacher facilitates discussion that reveal learners' understanding of new concepts, difficulties and creates conceptual conflicts that inform conceptual change.<br>• Representations are used for various purposes; engaging with prior knowledge, areas of difficulties and the development of new concepts. |

## Appendix iv: Baseline test

**Instructions and information**

- This paper consists of four questions, answer all of them.
- Number your questions the same way they are numbered on the question paper.
- Write neatly and legibly.

**QUESTION 1**

Write down one word or phrase described by the following statements.

1.1 The sign of the charge of a proton. (1)

1.2 The force between like charges. (1)

1.3 The unit of measurement of an electric charge. (1)

1.4 Materials that allow charges that move through them easily. (1)

**QUESTION 2**

2.1 A metal neutral ruler is rubbed with a cloth and it becomes positively charged. Which of the following statements is correct regarding charge on the ruler.

A. The ruler gained electrons.
B. The ruler gained protons.
C. The ruler lost electrons.
D. The ruler lost protons. (2)

2.2 When is an object electrically neutral?

A. When it doesn't contain protons and electrons.
B. When it has more protons than electrons.
C. When it has more electrons that protons.
D. When it has the same number of protons and electrons. (2)

2.3 A teacher demonstrated charging by friction by rubbing two rulers, one made of non-metallic material and the other made of metallic material, using a cloth. Which of the following rulers will be charged?

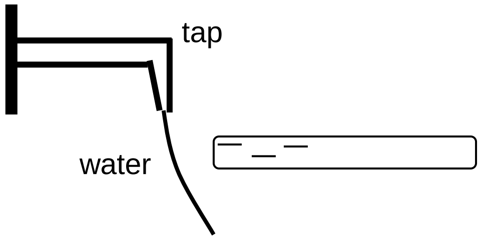
A. The metallic ruler only.
B. The non-metallic ruler.
C. Both
D. Neither (2)

2.4 State the law of conservation of electric charge. (2)

2.5 An electron has a charge of $1.6 \times 10^{-19}$ C. Is it possible to have an object with a charge of $1 \times 10^{-19}$ C? Defend your answer. (2)

## QUESTION 3

3.1 A learner in a Physical Sciences class rubs his hair with a plastic rod. The rod becomes negatively charged. The learner now opens a tap so that a thin stream of water runs from it. When the rod is brought close to the water without touching it, it is observed that the water bends toward the rod, as shown in the diagram below.

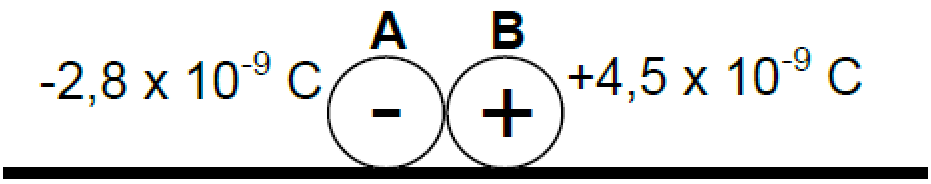



3.1.1 Give a reason why the stream of water bends towards the rod. (2)

3.1.2 If $10^{14}$ electrons are transferred to the rod, calculate the charge of the rod. (3)

## QUESTION 4

4.1 Two identical metal spheres, **A** and **B**, on an insulated surface carry charges of – $2.8 \times 10^{-9}$ C and + $4.5 \times 10^{-9}$ C respectively. The spheres are brought into contact with each other.




4.1.1 During contact, are electrons transferred from **A** to **B** or from **B** to **A**? (1)

4.1.2 It is observed that the spheres spontaneously move apart after contact. Briefly explain this observation. (3)

4.1.3 Calculate the new charge on each sphere after they have moved apart. (3)

## Appendix v: Baseline test memorandum

**QUESTION 1**

1.1 Positive ✓

1.2 Repulsive/repulsion ✓

1.3 Coulomb/C ✓

1.4 Conductors ✓

**QUESTION 2**

2.1 C ✓✓

2.2 D ✓✓

2.3 B ✓✓

2.4 The net charge of an isolated system remains constant during any physical process.✓✓

2.5 No✓. According to the principle of charge quantisation, charged objects contain charges that are multiples of the charge of an electron. ✓

**QUESTION 3**

3.1.1 The water gets polarised✓, meaning the negative end of a water molecule is repelled by the charge on the rod while the positive end is attracted. Therefore the charge on the rod attracts the water because it attracts the positive end of the molecules.✓

3.1.2 $Q = nq_e$ ✓

$Q = 1 \times 10^4 \times -1{,}6 \times 10^{-19}$ ✓

$Q = -1.6 \times 10^{-15}$ C ✓

**QUESTION 4**

4.1.1 A to B ✓

4.1.2 After the transfer of charges, the spheres will carry the same amount of charge✓. This will result in a repulsion✓, therefore the sphere will move apart.

4.1.3 $Q_{\text{on each}} = \frac{Q_1 + Q_2}{2}$ ✓

$Q_{\text{on each}} = \frac{(-2.8 \times 10^{-9}) + (4.5 \times 10^{-9})}{2}$ ✓

$Q_{\text{on each}} = 8.5 \times 10^{-10}$ C ✓

## Appendix vi: Performance test

### Instructions and information

- This question paper consists of two sections, A and B, and 4 questions.
- Please answer all the questions and number them as they appear in the question paper.
- Write neatly and legibly.

### SECTION A: MULTIPLE CHOICE QUESTIONS

### QUESTION 1

Choose the correct answer and write the corresponding letter in your answer booklet, e.g. 1.6 E. Please substantiate every option that you choose from 1.1 to 1.5.

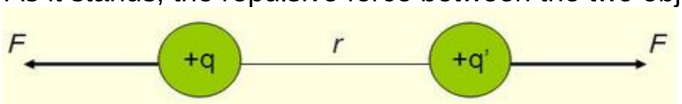
1.1 Two small objects each with a net charge of +Q exert a force of magnitude F on each other as shown below.


One of the objects is replaced with another objects whose net charge is +4Q.


The original force of +Q was F, what is the magnitude of the force on +Q after the replacement?

A. 16 F  B. 5 F  C. 4 F  D. F  E. $\frac{1}{4}$F  (2)

1.2 Two identically charged objects are placed a distance r apart as shown in the figure below. As it stands, the repulsive force between the two objects is F.




The objects are then moved apart such that the new distance between them is double the previous distance. What is the magnitude of the electrostatic force between them after the change in distance?

A. $\frac{1}{4}$F  B. $\frac{1}{2}$F  C. F  D. 4F  (2)

1.3 Two charged objects, X and Y, carry net charges of +Q and -2Q respectively. These objects are placed a few centimetres apart as shown in the diagram below.


Choose the pair of force vectors (the arrows) that correctly compares the electrostatic forces experienced by X and Y respectively.

A. X ⟶ ⟵ Y

B. X ⟶ ⟵ Y

C. X ⟶ ⟵ Y

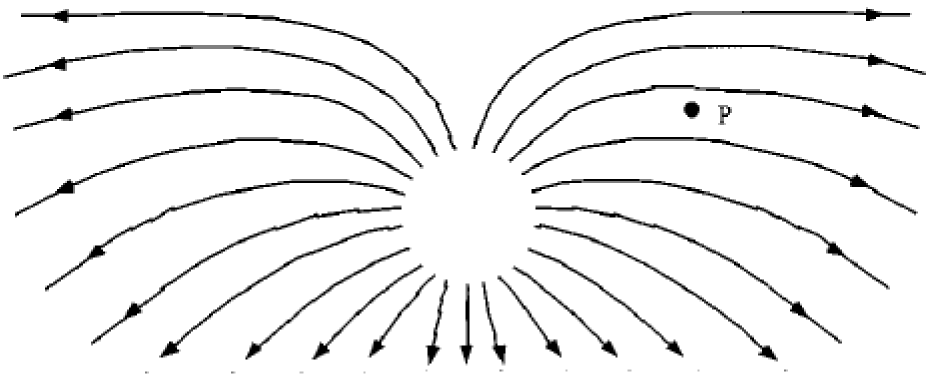
D. ⟵ X Y ⟶

E. ⟵ X Y ⟶

F. ⟵ X ⟵ Y

G. X ⟶ Y ⟶ (2)

1.4 Refer to the electric field below to answer the question that follows.

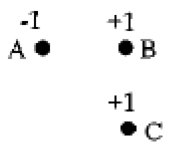



What is the direction of the electrostatic force on a negative charge placed at point P?

A. ⟵ B. ↙ C. ⟶ D. ↗ E. No force

(2)

1.5 Which of the following arrows indicate the direction of the net force on charge B?



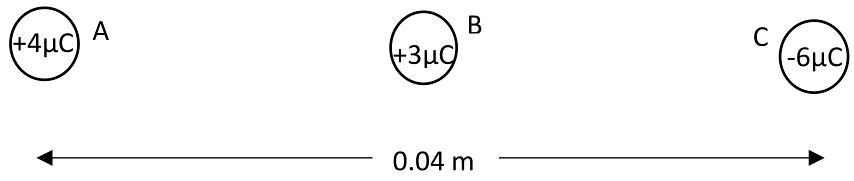

A. ⟵ B. ↑ C. ↖ D. ↗ E. ↙ (2)

**[10]**

## SECTION B

## QUESTION 2

2.1 Three charged spheres A, B and C with charges, +4µC, +3µC and -6µC respectively are positioned as shown in the diagram below. Sphere B is exactly halfway between sphere A and C which are 0.04 m apart from each other.




2.1.1 State Coulomb's law in words. (3)

2.1.2 Determine the magnitude and the direction of the force experienced by sphere B due to sphere A. (3)

2.1.3 Without using a calculator, write down the magnitude and the direction of the electrostatic force experienced by sphere A due to sphere B. (1)

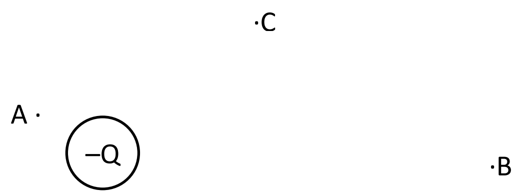
2.1.4 Determine the magnitude and the direction of the force experienced by sphere B due to sphere C. (2)

2.1.5 Determine the net force on sphere B due to sphere A and C. (2)

**[11]**

## QUESTION 3

3.1 A sphere with a net charge of – Q is surrounded by points A, B and C respectively as shown in the diagram below.




3.1.1 Describe an electric field in your own words. (2)

3.1.2 What is the direction of the electric field at point B? (1)

3.1.3 At which point is the electric field the weakest? Write A, B or C. (1)

3.1.4 Suppose identical point charges are now placed at the three points. At which point will the strongest electrostatic force be experienced? (1)

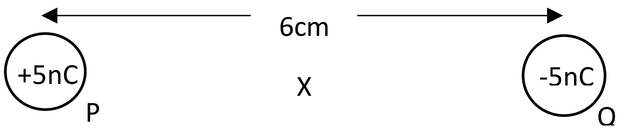
3.2 A negative point charge of magnitude $-2 \times 10^{-19}$ C is now placed at point B which is 3 mm to the right of the sphere. At that point, the point charge experiences a force of $4 \times 10^{-15}$ N.

3.2.1 Determine the magnitude of the electric field at point B. (3)

**[8]**

**QUESTION 4**

4.1 Two small charged particles, P and Q, are placed on a straight line 6 cm apart. The charge on P is +5 nC and the charge on Q is -5 nC. X is a point exactly halfway between the two small charges.




4.1.1 Draw the resulting electric field pattern of the charged particles. (3)

4.1.2 Determine the magnitude and the direction of the electric field at point **X** due to charge **P**. (3)

4.1.3 Determine the magnitude and the direction of the electric field at point **X** due to charge **Q**. (2)

4.1.4 Determine the net electric field at point **X** due to charge **P** and charge **Q**. (2)

4.1.5 Suppose the two spheres were both positive with equal magnitudes, what would be the magnitude of the net electric field at point **X**? Defend your answer. (3)

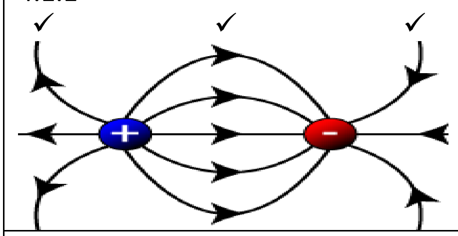
**[13]**

**Total: 42**

## Appendix vii: Performance test memorandum

The table below is divided into two parts. Correct answers to the test questions are indicated on the left while the skills and the understanding that is demonstrated by the correctness of learners' answers are described on the right.

| | |
|---|---|
| **Question 1: Multiple choice questions** | |
| 1.1) C ✓✓ | The force is directly proportional to the products of the charges. Since the product is 4, the force becomes 4 times stronger. |
| 1.2) A ✓✓ | The force is inversely proportional to the squared distance, therefore the force becomes $½^2$ weaker. |
| 1.3) B ✓✓ | The objects are oppositely charged hence they are attracting, and according to Newton's third law, the exert equal but opposite forces on each other. |
| 1.4) A ✓✓ | The given electric field surrounds a positive charge, therefore the negative charge will be attracted to it. Those who select B can be given the benefit of the doubt. |
| 1.5) C ✓✓ | Charge B is attracted to the left by charge A while charge C repels it upwards. The net force is therefore in quadrant 2. |
| 2.1.1) The law is stated. | The ability to recall coulomb's law which states that; the force of interaction between charged objects is <u>directly proportional to the products of the charges✓</u>, and <u>inversely proportional✓</u> to the <u>squared distance✓</u> between their centres. |
| **Question 2: Open ended questions** | |
| 2.1.2)<br>$F = k\frac{Q_1Q_2}{r^2}$✓<br>$F = (9x10^9)\frac{(4x10^{-6})(3x10^{-6})}{(0.02)^2}$✓<br>$F = 270$ N to the right ✓ | The ability to apply coulomb's law and realising that sphere A and sphere B are both positive, therefore they are repelling each other. Hence sphere A pushes sphere B to the right. |
| 2.1.3) 270 N to the left ✓ | The application of Newton's third law; the forces are equal in magnitude but opposite in terms of direction. |
| 2.1.4) $F = k\frac{Q_1Q_2}{r^2}$<br>$F = (9x10^9)\frac{(4x10^{-6})(6x10^{-6})}{(0.02)^2}$✓<br>$F = 405$ N to the right ✓ | Similar to 2.1.2. However, learners will be demonstrating an understanding that they should not substitute negative charges in their calculations. Sphere C is negative while sphere B is positive, this means that C is attracting B towards itself. Hence the direction is to the right. |
| 2.1.5) $F_{net} = F_{A\ on\ B} + F_{C\ on\ B}$ ✓<br>$F_{net} = 270 + 405$<br>$F_{net} = 675$ N to the right. ✓ | The ability to add vectors. Both vectors are in the same direction, to the right, hence they add up. |
| **Question 3: Open ended questions** | |
| 3.1.1) Possible explanations are given. | An electric field is a region of space where an <u>electric charge✓</u> experiences an <u>electrostatic force✓</u>. |

| | |
|---|---|
| | The strength of the field at a point is determined by the force per unit charge at that point. |
| 3.1.2) B ✓ | The electric weakens with distance from its source. Point B is far from the charge, therefore the field strength is weaker there. |
| 3.1.3) A ✓ | The electric field is directly proportional to the electrostatics force. The field is stronger at point A because it is closer to charge –Q, hence the force is also stronger at that point. The correctness of this answer could also stem from the application of coulomb's law. |
| 3.2.1) Left ✓ | Electric field lines are always towards a negative charge. Point B is to the right of the charge, therefore the field at that point is to the left. |
| 3.2.2)<br>$E = \frac{F}{q}$ ✓<br>$E = \frac{4\,x10^{-15}}{2\,x10^{-19}}$ ✓<br>$E = 20\,000\ N.C^{-1}$ ✓ | The ability to apply a formulae that helps solve problems related to electric field strength based on the information provided. |
| **Question 4: Open ended questions** | |
| 4.1.1<br> | Field lines are always drawn from a positive charge towards a negative charge. They neither touch nor cross. |
| 4.1.2)<br>$E = k\frac{Q}{r^2}$ ✓<br>$E = (9x10^9)\frac{5x10^{-9}}{(0.03)^2}$ ✓<br>$E = 5x10^4\ N.C^{-1}$ to the right ✓ | The ability to convert different units of measurements, from nC to C and from cm to m. Particle P is positively charged, hence its electric field is away from it. Point X is placed to the right of the particle, hence the direction of the field there is to the right. |
| 4.1.3)<br>$E = k\frac{Q}{r^2}$<br>$E = (9x10^9)\frac{5x10^{-9}}{(0.03)^2}$ ✓<br>$E = 5x10^4\ N.C^{-1}$ to the right ✓ | Similar to 4.1.2. However, learners demonstrate the understanding that they must not substitute signs in their calculations. Particle Q is negative and its electric field is towards it. Point X is to the left of this field, hence the direction of the field at that point is to the right. |
| 4.1.4) $E_{net} = E_p + E_q$ ✓<br>$E_{net} = 5x10^4 + 5x10^4$<br>$E_{net} = 1x10^5 N.C^{-1}$ to the right ✓ | Similar to 2.1.5. The ability to add vectors. |
| 4.1.5) Zero ✓ | Both particles carry the same charge of the same magnitude, <u>hence their electric fields are in opposite directions</u> ✓. <u>At point X, which is exactly halfway, the fields cancel out</u> ✓ and the net is zero. |

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## Appendix viii: GDE permission letter

Dear Sir/Madam

**Permission to conduct research in Tshwane District schools**

I am hereby applying for permission to conduct research in Tshwane district schools. The aim of the project is to investigate the relationship between teachers' pedagogical content knowledge (PCK) about electrostatics and learners' performance in the topic. Thus it is imperative that I collect data reflecting teachers' PCK and learners' performance.

Data will be collected during the semester of teaching practice, a period where fourth year B.Ed. students teach for assessment in various schools. As such, pre-service teachers will be invited to participate alongside in-service physical sciences teachers. The learners that will be taught by the teachers will also be invited to participate in the study. Data that reflects the PCK of the teachers will be collected using a content representation (CoRe) tool, lesson plans, lesson observations and interviews. The data collection will not interfere with the normal day to day running of the schools. The teachers will complete the CoRes and lesson plans during their own time. Furthermore, they will be interviewed in a time and place that suits them best. The lessons of the teachers will be recorded without any interference from the back of the class to ensure that learners' faced don't show. However, I will ask the schools permission to let their learners write two tests that the schools can use as formative and/or summative assessment.

The data collected in this study and the identities of the participants and their affiliated institutions will be kept confidential and will be used solely for the purpose of this research. Furthermore, I will use pseudonyms in the dissemination phase of the research findings.

Please find my full proposal attached for further details on this study

Yours sincerely

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## Appendix ix: Dean of education permission letter

Prof Chika Sehoole
Dean Faculty of Education
University of Pretoria

Dear Prof Sehoole

**Request to involve 4th year BEd methodology students as participants in a PhD research project**

I am currently registered for a PhD at the University of Pretoria under the supervision of Prof. Estelle Gaigher and Dr. Corene Coetzee. My PhD research project is entitled: **The relationship between teachers' pedagogical content knowledge about electrostatics and learners' performance.**

Pedagogical Content Knowledge (PCK) describes the amalgam of content and pedagogy and is therefore regarded as a knowledge base possessed and utilized by effective teachers. In this project I intend to investigate the influence of teachers' PCK on learners' outcomes in electrostatics. According to the physical sciences CAPS document, electrostatics is taught at grade 11 in the third term, a period which coincides with the teaching practice period of students in the Faculty of Education. As a teacher trainer involved in the mentoring of pre-service teachers during the teaching practice period, I would like to invite the students that will be teaching physical sciences to participate in my research project. The role of the pre-service teachers will be:

- To complete a content representation (CoRe) tool. A CoRe tool is an instrument that captures teachers' PCK by prompting them to articulate it in writing. In this study it will be used to capture the PCK of pre-service teachers about electrostatics.
- To teach the topic of electrostatics to completion while they are observed and video recorded as part of the normal interaction between students and mentor lecturers during the teaching practice period.
- To participate in a video stimulated recall (VSR) interview. The aim of the interview is to allow the pre-service teachers to review their own lessons and describe their thoughts that led to certain observable pedagogical actions.

There are seven students enrolled for the fourth year physical sciences methodology module (JMN 433) this year. I am hereby requesting your permission to involve these students as participants in my study. Consent will be requested from the students because participation is at free will. Furthermore, the identities of the students will be hidden at all times.

Your consideration of my request will be highly appreciated.

Yours sincerely

…………………………………………………….

Ernest Mazibe

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## Appendix x: Principal permission letter

The principal

ABC School

Pretoria

**Request for permission to conduct research in your school**

I am hereby requesting permission to conduct research that investigates the relationship between teachers' pedagogical content knowledge (PCK) about electrostatics and learners' performance in your school.

This study involves in-service and pre-service physical sciences teachers together with their learners. You are receiving this letter because your school is either hosting a physical science pre-service teacher or because one of your staff members is a potential candidate to participate as an in-service teacher in this study. Should permission be granted, the participating teachers will be requested to complete a content representations (CoRe) tool, teaching the topic of electrostatics at grade 11 while they are video recorded, and participate in an interview. The data collection processes will not interfere with the normal day to day running of the school. The lessons will be recorded from the back of the class to ensure that the faces of the learners do not show in the video. The interviews will be held outside of the school hours in a time and a place that suits the teacher. I would also like to request that learners write two tests that I have developed for this study. The tests are set relative to the standard of the department of education and can therefore be used as formative and summative assessment.

The data collected in this study as well as the names of the participants and their affiliated institutions will be kept confidential at all times and will be used solely for the purpose of this research. Pseudonyms (false names) will be used when findings are disseminated at the end of this study.

Please complete the form below to indicate your decision regarding this request.

I, _______________________________________________________ (your name and surname), the principal of _______________________________________________________ (your school's name), grant/do not grant (delete the one that is not applicable) permission to have the above study conducted in my school.

Principal's signature: ________________________________________ Date: ______________________

Researcher's signature: ______________________________________ Date: ______________________

Supervisor's signature: _______________________________________ Date: ______________________

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## Appendix xi: Pre-service teacher consent letter

Dear 4th year student

**Informed consent to participate in a research study**

You are hereby invited to participate in a research study that investigates the relationship between teachers' pedagogical content knowledge (PCK) about electrostatics and learners' performance in the topic.

You have been selected as a potential participant because you are a fourth year student studying towards a B.Ed. degree and your specialisation includes physical sciences. Furthermore, during the teaching practice internship you will present lessons in the presence of a mentor lecturer who will assess your teaching expertise. I am a mentor lecturer in your university and I am asking for your consent to be my mentee during the teaching practice internship and to participate in this research study.

Your primary role in the research, should you willingly participate, includes sharing your PCK about the topic of electrostatics. You will be expected to complete a content representation (CoRe) tool, teach the whole topic of electrostatics in my presence while you are video recorded, and participate in an interview. Your involvement in this study will not interfere with the teaching practice internship and the normal routine of your school as you will complete the CoRe tool and be interviewed in your own place and time. Furthermore, electrostatics is taught during the third term as stipulated in the CAPS document, the same period in which this study will be undertaken. I would also like to explore your learners' performance and understanding of the topic before and after you have completed teaching it as part of their normal formative and/or summative assessment.

All the data collected in this research as well as your identity and that of your school will be kept confidential at all times. Furthermore, the data will be used solely for the purpose of this study while pseudonyms will be used in the dissemination phase of the findings. You have the right to decline or withdraw your participation even after giving consent in this study without any repercussions. Your involvement in this study is voluntary.

Please complete the consent form to indicate your decision about your involvement in this study.

I, ____________________________________________________ (initials, surname and student number) am willing/not willing (delete the one that is not applicable) to participate in the study advertised above. I am aware of my role in this study and I understand the following ethical principles:

- I am not forced to participate in this research, I am participating willingly.
- I am not forced to be involved throughout the progress of the study, I can discontinue at any time at free will without any repercussions even after giving consent in this document.
- All the data collected by the researcher will be kept confidential and used solely for the purpose of the advertised research study.
- My identity and those of my affiliated institutions, including learners, will be kept confidential at all times. Pseudonyms will be used in the dissemination of the findings.

4th year student's signature: _______________________________ Date: __________________

Researcher's signature: __________________________________ Date: __________________

Supervisor's signature: __________________________________ Date: ___________________

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## Appendix xii: Mentor teacher permission letter

Dear mentor teacher

**Permission to conduct research in your class**

You have been assigned a fourth year student from the University of Pretoria to mentor during the teaching practice internship. The student is a participant in a research study that investigates the the relationship between teachers' pedagogical content knowledge (PCK) about electrostatics and learners' performance in the topic. I am hereby asking for your permission to conduct this research in your classroom, involving the student teacher and your learners. This research will not interfere with the normal school routine as electrostatics is scheduled to be taught in the semester of teaching practice. However, I would like to request that you to allow the student teacher teach the whole topic of electrostatics. This is particularly important because the purpose of the study is to investigate the student teachers' unaided influence on learners' understanding of electrostatics. All the lessons of the students will be video recorded from the back of the class to ensure that learners' identities are hidden. I would like to assess your learners' understanding of electrostatics before and after the student has taught this topic to completion as part of their normal formative and/or summative assessment. The data that will be collected in your classroom, the identity of the participants and your school will be kept confidential at all times. You have the right to decline this request even if the student has given consent to participate.

Please complete the form below to indicate your decision regarding this request.

I, ______________________________________________________________ (Your initials and surname) grant/ do not grant (delete the one that is not applicable) permission to have the study advertised above conducted in my classroom.

Mentor teacher's signature: _______________________________ Date: ________________________

Researcher's signature: ___________________________________ Date: ________________________

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Supervisor's signature: _________________________________ Date: _______________________

## Appendix xiii: In-service teacher consent letter

Dear grade 11 physical sciences teacher

**Informed consent to participate in a research study**

You are hereby invited to participate in a research study that investigates the relationship between teachers' pedagogical content knowledge (PCK) about electrostatics and learners' performance in the topic. PCK refers to the transformation of raw content into teachable forms.

Your primary role in this research, should you willingly participate, includes sharing your PCK about the topic of electrostatics. You will be expected to complete a content representation (CoRe) tool, teach the topic of electrostatics at grade 11 while you are being video recorded and to participate in an interview. Your involvement in this study will not interfere with the normal day to day running of your school. You will complete the CoRe tool and be interviewed in a place and time of your choice. I would also like to ask for your permission to administer two tests to your learners on electrostatics. The tests are set relative to the standard of the department of education and can therefore be used as a formative or summative assessment.

All the data collected in this research as well as your identity and that of your school will be kept confidential at all times. Furthermore, the data will be used solely for the purpose of this study while pseudonyms will be used in the dissemination phase of the findings. You have the right to decline or withdraw your participation even after giving consent in this study without any repercussions. Your involvement in this study is voluntary.

Please complete the consent form to indicate your decision about your involvement in this study.

I, ______________________________________________________ (initials, surname and student number) am willing/not willing (delete the one that is not applicable) to participate in the study advertised above. I am aware of my role in this study and I understand the following ethical principles:

- I am not forced to participate in this research, I am participating willingly.
- I am not forced to be involved throughout the progress of the study, I can discontinue at any time at free will without any repercussions even after giving consent in this document.
- All the data collected by the researcher will be kept confidential and used solely for the purpose of the advertised research study.
- My identity and those of my affiliated institutions, including learners, will be kept confidential at all times. Pseudonyms will be used in the dissemination of the findings.

4th year student's signature: ________________________________ Date: __________________

Researcher's signature: ____________________________________ Date: __________________

Supervisor's signature: ____________________________________ Date: ___________________

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## Appendix xiv: Parent/Guardian permission letter

Dear parent or guardian

**Request for consent for minors to participate in a research study**

Your child who is in grade 11 is currently taught by a teacher who is participating in research. The aim of the study is to investigate how science is being taught in schools and how learners understand it. I would like to ask your permission to allow your child to participate in this study. For this research to be a success I have to video record the lessons of the teacher. All the videos will be recorded from the back of the class to ensure that your child's face is hidden. If your child turns and shows his or her face, I will block it on the video. Your child will also write two tests as in the normal school routine. I am also asking for your permission to use the marks that your child obtains in the tests. The marks will not be shared with anyone and I will use them for this research project. You have a right to decline this request. This means that I will not record your child in the video, and I will not use the marks that your child gets in the tests.

Please complete the form below to indicate your decision regarding this request.

I, ____________________________________________________________ (name and surname), parent of ____________________________________________________________ (your child's name and surname) am granting/not granting (delete the one that is not applicable) my child permission to participate in this study.

Parent or guardian signature: __________________________________ Date: ______________________

Researcher's signature: _______________________________________ Date: ______________________

Supervisor's signature: ________________________________________ Date: ______________________

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## Appendix xv: Learner assent letter

Dear grade 11 learner

**Request for assent to participate in a research study**

You are hereby invited to participate in a research study. The aim of the research is to investigate how your teacher teaches the topic of electrostatics. You have been selected as a participant because you are in grade 11 and one of your subjects is physical science. I would like to explore your understanding of electrostatics before and after it has been taught by your teacher. I will take videos of the lessons from the back of the class to ensure that your face is hidden. If your face shows in the video then I will block it. As part of the normal formative and summative assessment of your school, you will write two tests contributing towards your final mark for physical sciences. The first test will explore your prior knowledge of the topic and will be written before you learn about electrostatics while the second test will be written once the topic of electrostatics has been taught to completion. I am asking for your permission to use your marks in this research project. If you decline this invitation, I will not use your marks for the purpose of the research although they will still contribute towards your final mark. If you give permission, I will use your marks for the purpose of this research and I will not share them with anyone.

Please complete the form below to indicate you decision regarding this invitation.

I, ________________________________________________ (Your name and surname) am willing/am not willing (delete the one that is not applicable) to participate in the research study advertised above. I understand that participation is voluntary and I can discontinue my involvement in this study at any time even after giving assent in this document. I also understand that my marks will be confidential and used solely for the purpose of this research.

Grade 11 learners signature: _______________________________________ Date: _________________

Researcher's signature: ___________________________________________ Date: _________________

Supervisor's signature: ___________________________________________ Date: __________________