

Enhancing understanding of conceptual relationships in introductory mechanics

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ABSTRACT

For more than four decades researchers in the field of introductory mechanics have investigated ways to develop student understanding of physics concepts and overcome deficiencies in student ability to apply physics knowledge in everyday contexts. However, a core research problem that remains is that only limited success has been obtained in addressing the difficulties students experience when learning classical mechanics, especially with regard to acceleration and free-fall motion. The large body of literature confirms that conceptions arising from student everyday experiences and the ways they seek to make sense of these experiences contribute to many conceptual difficulties.

The research reported in this thesis is motivated by the desire to improve specific aspects of the teaching of some core concepts and relationships in introductory mechanics, with particular focus on motion under gravity and net force-mass-acceleration relationship expressed in Newton's second law. The research has focused on circumstances which could potentially enhance understanding of conceptual relationships and concepts for motion under gravity. The circumstances investigated were:

- Considering the impact of a simplification of physics *per se*
- Using multiple representations
- Qualitative (proportional) reasoning / using equations as reasoning tools
- A qualitative approach to teaching acceleration

The research has followed a Design-Based Research approach. This methodology was chosen for its use of iterative cycles of design and evaluation of solutions to practical problems. The different iterations of the study, some qualitative and some quantitative, were conducted with different research groups of physics learners, as individual investigations. The results of the iterations indicate that attention to the four circumstances mentioned above, as applied in the research, did in fact enhance student understanding of the concepts and conceptual relationships of motion under gravity.

Two outcomes of the research have specific value beyond this study, namely a qualitative approach to teaching acceleration as the net force to mass ratio and a graphical tool to help students understand the effect of air resistance on falling objects and the concept of free fall. In addition to these outcomes, a set of design principles is presented which can inform the design of topic specific teaching interventions.

Keywords: simplification, conditional statements, conceptual change; force-mass-acceleration, qualitative reasoning, equations, multiple representations, free fall, teaching sequence, design principles.

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CHAPTER 1: INTRODUCTION AND PROBLEM STATEMENT

1.1 Introduction

Research in physics education has long been concerned with the problem that students, through their interactions with their daily world, acquire conceptions that are unsatisfactory from a scientific point of view. Physics is based on a small number of concepts and their interrelationships that form the foundation for various applications (Van Heuvelen 1991; Duschl, Maeng & Sezen, 2011). Knowledge and mastery of these fundamental concepts, particularly in mechanics, is essential to students' performance in their school, undergraduate, and more advanced physics and engineering courses (Hedge & Meera, 2012; Williamson, Prather & Willoughby, 2016). Learning concepts in physics is, however, difficult due to the often simultaneous presence of misconceptions and alternative conceptions, frequently derived from their daily experiences and very resistant to teaching that seeks to change them (Clemens & Andreas, 2014). With its many overlaps with everyday life, understanding mechanics has proven particularly challenging (Nieminen, Savinainen & Viiri, 2010; Shtulman & Valcarcel, 2012). For more than four decades researchers in the field of introductory mechanics have investigated ways to seek to develop better student understanding of physics concepts and to overcome deficiencies in student ability to apply physics knowledge in everyday contexts.

A substantial body of research in physics education shows that for many students the development of deep understanding (of the contextual character of core concepts and the empirical and fundamental relationships between those concepts) (Svensson, 1989), specifically in mechanics, remains extremely difficult (for example, see four extensive reviews of this and related research in Driver and Erickson (1983); Gilbert and Watts, 1983; Duit, 2009; Duit, Schecker, Höttecke and Niedderer, 2014). Poor student performance on problems set in real world contexts highlights conventional instruction's failure to identify, much less address, ineffective tuition practices (Gunstone & White, 1981; McDermott, 1984; Von Aufschnaiter & Rogge, 2015). In the specific area of mechanics concerned with acceleration, force and motion in free fall this failure is particularly obvious. In this topic there has been only very limited success obtained with attempted solutions to the persistent learning difficulties students continue to experience over the decades. It is this content area that is the focus of the research proposed, described, and reported in this thesis.

1.2 Background and motivation

While some researchers regard the topic of mechanics as over-researched, studies continue to reveal the persisting influence of student alternative conceptions on both their conceptual

understanding (or lack thereof), and their view of the relevance of physics in their daily lives (Rebello & Rebello, 2013; Muis & Gierus, 2014). Various researchers argue that the main goal of an introductory physics course should be helping students to develop both a good understanding of physics concepts and the ability to use that understanding to solve physics problems (e.g. Champagne, Klopfer & Gunstone, 1982; Halloun & Hestenes, 1985; McDermott & Shaffer, 1992; Duit, 2009; Von Aufschnaiter & Rogge, 2015). However, physics education research has consistently shown for more than three decades that teachers often fail to develop student understanding of physics concepts (Champagne *et al.*, 1982; Halloun & Hestenes, 1985; McDermott & Shaffer, 1992; Duit, 2009; Von Aufschnaiter & Rogge, 2015).

Traditional forms of teaching very often fail to help students to understand physics concepts, or to enable students to use their knowledge to analyse new physics situations effectively (e.g. Hammer, 1996). Researchers have proposed different detailed teaching models for physics education during the previous decades, the first likely being in the early 1980s (Champagne *et al.*, 1982). However, it is only recently that researchers have started to relate current physics learning research with the results and analyses reported in the earlier years. For example, an increasingly stronger focus on the design and implementation of detailed teaching-learning sequences that focus on the improvement of student understanding can be seen in the work of Duit *et al.* (2014), Leach and Scott, (2002), Tiberghien Vince and Gaidioz, (2009) and Von Aufschnaiter and Rogge (2015). In South Africa the 2013 progress report of the National Education Evaluation and Development Unit (NEEDU) to the South African Parliamentary Monitoring Group stated that “new, innovative and effective teaching techniques need to be adopted to overcome the inherent deficiencies in students entering the undergraduate physics programme” (SAIP 2013:34). The NEEDU report calls for “the development of particular teaching approaches and strategies most appropriate for inculcation of the (unique) concepts that constitute the discipline” (SAIP 2013:27).

Despite the acknowledged and profound deficits in learning resulting from traditional teaching, the rate of adoption of the few successful research-based instructional approaches and strategies in the subject of physics remains low. While various researchers have, for example, investigated and reported on learning progressions for different physics topics to develop conceptual understanding of physics principles (Duschl *et al.*, 2011; Tiberghien *et al.*, 2009; Von Aufschnaiter & Rogge, 2015), there is a lack of teaching approaches and strategies that use student intuitive knowledge as anchors to bring about conceptual change and to develop or enhance conceptual understanding of specific fundamental concepts.

Physics education research has revealed that conceptions arising from student everyday experiences and the ways they seek to make sense of these experiences contribute to many

conceptual difficulties students have when learning physics. Many studies have reported that student conceptual development is related to both their cognitive understanding of individual physics concepts and their epistemological beliefs about physics (e.g. Chu, Treagust & Chandrasegaran, 2008; Chu & Treagust, 2014; Duit *et al.*, 2014). Student perceptions of the nature of physics knowledge effect many aspects of their physics learning (Chu *et al.*, 2008; Duit *et al.*, 2014; Muis & Gierus, 2014; Von Aufschnaiter & Rogge, 2015), for example their reasoning about physical situations and the extent to which they are willing to recognize, evaluate and reconstruct those ideas (Gunstone, 1992). This is a particularly significant aspect of the learning of mechanics. The research reported in this thesis is motivated by the desire to improve specific aspects concerning the teaching of some core concepts and relationships in that component of introductory mechanics concerned with motion under gravity and the poorly understood net force-mass-acceleration relationship expressed in Newton's second law.

1.3 The research problem

The research problem under investigation in this thesis emanated from my Master of Science Education study (Ferreira, 2014), in particular, the difficulties caused by conditional statements that are intended to simplify real world situations and the learning consequences of such simplifications. The results of that research showed that students in introductory physics courses, assumed to have a good understanding of the concept of acceleration based on their schooling, still did poorly on some diagnostic questions. The Master's study concerned objects in free fall, i.e. objects for which it was assumed gravitational force was the only force acting. The conditions of "ignore air resistance and friction opposing motion" were clearly stated in each item of the questionnaire from which the data for the Master's study were obtained. In addition to highlighting the persistence of the alternative conception that "heavier objects fall faster", responses to the multiple-choice items also revealed other interesting tendencies in students' thinking. For example, it was shown that the direction of motion had a practically significant influence on student choice of either the correct option or the alternative "heavier falls faster" option. Students did not apply the concept of free fall consistently across each of the three contexts of vertical motion up, vertical motion down, and motion on an inclined plane. The physics variable to be solved for in an item also had an influence on the option chosen for that item: items requiring comparison of the time of the falling objects had a higher percentage correct response than items where other variables were required, e.g. speed or distance. These results indicated that students did not interpret the conditional statements correctly and that this impacted on their understanding of the concept of free fall motion. A report of the study has been published in the proceedings of the 2015 conference of the European Science Education Research Association (ESERA) and is included in this thesis as Ferreira and Lemmer (2016) in Appendix A.

1.4 Research aims and objectives

The aim of the present study in the context of introductory mechanics is twofold; to i) investigate and identify circumstances in the context of the topic of motion in free fall in introductory mechanics that will foster better understanding of concepts and conceptual relationships relevant to objects in free fall motion, and ii) to incorporate these circumstances in the design of educational intervention-based solutions intended to address the research problem. Central to this approach to foster better understanding of specific mechanics relationships is clarifying the use of conditional statements and enabling students to combine the affordances of multiple representations of said relationships in qualitative reasoning. This will be approached by exploration of the circumstances that promote conceptual change and qualitative reasoning in this topic in mechanics and thus also adding to students' perceptions of physics as a whole as a coherent body of knowledge.

1.5 Research questions

The main research question driving this study is: What circumstances will foster better understanding of concepts such as acceleration and its conceptual relationships, in the topic of motion in free fall? The two aspects of importance in the research question that need further clarification are 'circumstances' and 'conceptual relationships'. It is important to note that conceptual relationships can be formulated at different levels of precision: a qualitative level (for example, 'there is no acceleration if the net force acting upon an object is zero'), a semi-qualitative level (for example, for the same force acting on objects the magnitude of acceleration decreases for objects of greater mass), and a quantitative level (for example $F_{net} = ma$). The circumstances that influence the poorly understood concept of acceleration and its conceptual relationships to be investigated are:

- Considering the impact of simplification on concept learning;
- Using multiple representations in a deliberately designed sequence to maximise their affordances;
- A conceptual versus a kinematic perspective to teaching acceleration; and
- Using equations as reasoning tools, specifically regarding qualitative (proportional) reasoning.

The complexity of the research question required that different aspects of possible solutions had to be developed, tested and the consequences analysed in an iterative process. Each one of the iterations was guided by a research question[s] formulated based on the findings of previous

iteration(s). I chose to refer to the questions that guided a particular iteration as “detailed” questions and not as “sub-questions” to prevent any implication that the detailed questions were somehow less important than the main research question. The detailed research questions evolved as the investigation around the circumstances that influence the learning of challenging concepts in introductory mechanics, proceeded. The detailed research questions presented in Section 1.7 reflect the iterative nature of the research design and the evolution of the detailed research questions over time.

After identifying the research problem and main research question, the scope of this research is defined as to better support the learning of challenging concepts related to acceleration in introductory mechanics, therefore, only fine grained learning and teaching processes are considered. Fine grained learning and teaching processes include certain flow of activities and interaction implemented by students and teachers to achieve some short-term goals (e.g. mastering of a topic/lesson). Large grained learning processes on the other hand are attempting to be much more generic and therefore not helpful for considering the learning and teaching of specific concepts and relationships already known to present persistent problems.

1.6 Research methodology

The nature of the research requires an approach chosen on the basis of its functionality. Design-based research (DBR) is a flexible methodology that can yield both quantitative and qualitative data collected using a variety of methods and techniques. The freedom of choice in the methods, procedure and the techniques of research that best fitted the needs and purposes of the present study (Alghamdi & Li, 2013), combined with the research purpose of designing an educational intervention that takes various circumstances identified to influence concept learning into account, lead me to DBR as methodology. Figure 1-1 below is a time-line of the consecutive iterations of the DBR, as described in Chapter 3 and for which greater detail is given separately for each iteration in Chapters 4 to 8.

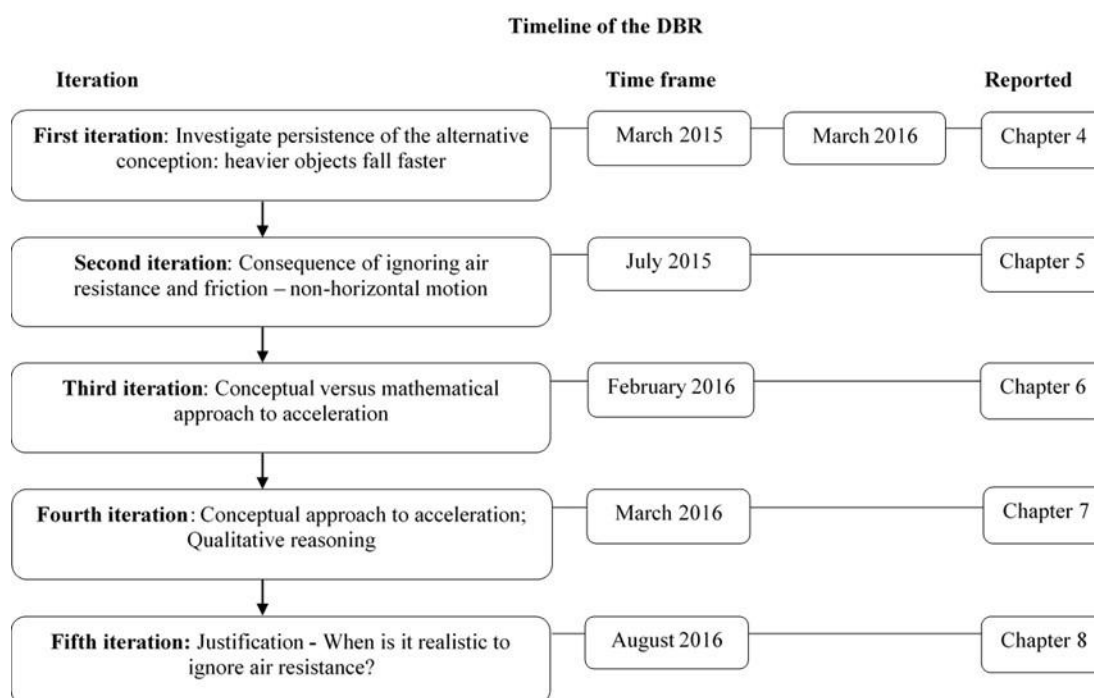


Figure 1-1: Timeline of DBR

1.7 Overview of thesis

In this section I present a brief outline of the content of the different chapters of this thesis.

1.7.1 Chapter 1: Introduction and problem statement

This chapter presents the background for the research problem, the formulation of the research question and a rationale for the study and its context.

1.7.2 Chapters 2: Literature review

In Chapter 2 I present literature from the existing body of knowledge that supports the rationale for the study. Chapter 2 sets the study against the broad background of education and places the study in the domain of physics education. Detailed literature concerning issues specific to the teaching and learning of the aspects of physics on which this research is focussed, is presented.

1.7.3 Chapter 3: Research design and design principles

In Chapter 3 an overview of the philosophical assumptions underpinning the DBR methodology is given and the design principles, as inferred from the literature and how they applied to the different iterations, are made explicit. Both the merits of DBR as research design and how DBR is used in this study in particular are discussed and justified. Only a brief outline of the iterations and data analyses is given, as full details of sampling, research instruments, data collection and

analysis for each iteration are presented in the chapters about each of the individual iterations. The number of significant figures used in reporting the statistics differs according to the number obtained from the analysis programme used; two significant numbers were chosen for the T-test, Cohen's d, and three significant numbers were chosen to report the results of the chi-squared test, Cramer's V. Figure 1-2 is a diagrammatic overview of the consecutive iterations of the DBR as presented in Chapter 3.

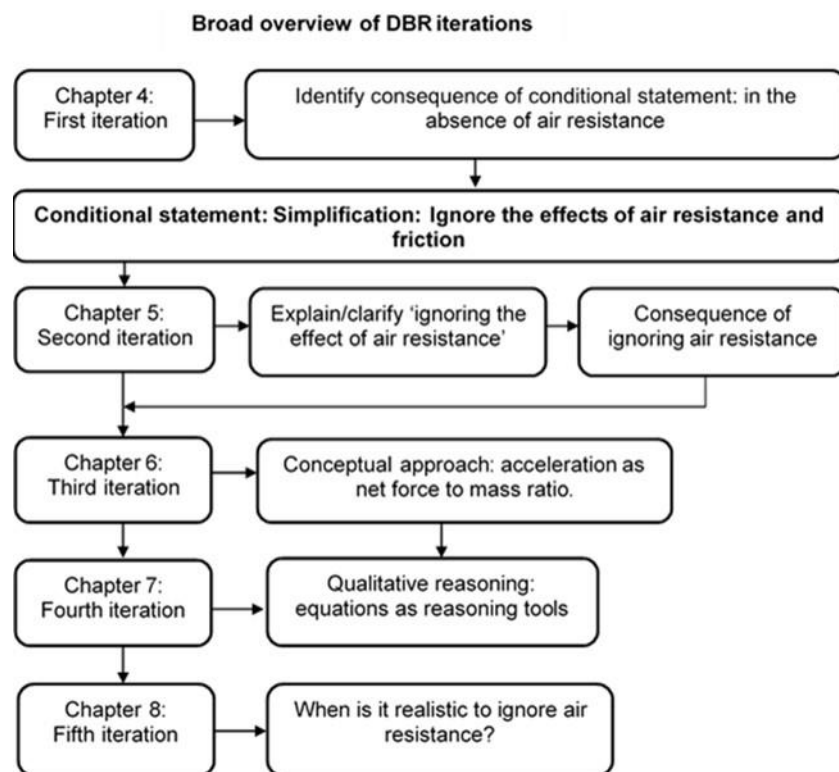


Figure 1-2: Diagrammatic overview of the iterations of the DBR

1.7.4 Chapter 4: First iteration

Chapter 4 reports on the quasi-longitudinal study that flowed from prior research conducted as part of my Master's study. The results of the Master's research were tested with two new cohorts of students (2015 and 2016 respectively) to determine the extent of the research problem. The results informed the DBR to develop solutions with practical use to enhance understanding of conceptual relationships in motion under gravity. The results of this iteration have been published in Ferreira, Lemmer, and Gunstone (2017), and is included in Chapter 4.

1.7.5 Chapter 5: Second iteration

The detailed research question that drove this iteration was: To what extent does (a) explanation of simplification statements and (b) the use of multiple representations of linear motion contribute

to student understanding of (i) acceleration as the net force- mass relationship, and (ii) the conceptual relationships between the physics variables for motion under gravity?

A detailed report on the second iteration, including the research population, research instruments, data collection and analysis is presented in this chapter. Based on the results obtained in this iteration, seeking to explain simplification as a circumstance became a crucial part of each of the subsequent iterations.

1.7.6 Chapter 6: Third iteration

The detailed research question guiding the third iteration was: What is the effect of a conceptual teaching approach to acceleration as the net force to mass ratio on i) student understanding of the concept of acceleration and ii) their use of qualitative proportional relationships of Newton's second law? The chapter reports on the implementation and consequences of the iteration, a qualitative study.

1.7.7 Chapter 7: Fourth iteration

The detailed research questions for this fourth iteration were: i) How will an approach, consisting of an alternative representation of acceleration as the net force to mass ratio, influence students' conceptual understanding of the concept of acceleration; and ii) How will blending of multiple representations¹ and introducing equations as reasoning tools in qualitative reasoning influence student understanding of the conceptual relationships represented by equations? These questions were explored via a quantitative study.

1.7.8 Chapter 8: Fifth iteration

The detailed question for this final iteration was: What are the specific circumstances under which it is realistic to ignore the effect of air resistance on falling bodies? In this chapter I report on the development of a graphical tool with which students can quantify the significance of the impact of air resistance on motion under gravity of various everyday objects. The results of this iteration have already been published as Ferreira, Seyffert, and Lemmer (2017) and is included in Chapter 8.

1.7.9 Chapter 9: Conclusion

In Chapter 9 a brief overview of the research and how DBR was used in this study is given. In addressing the research questions, conclusions are drawn for each iteration to support

¹ Combining affordances of various representations

recommendations for alternative teaching or learning strategies and approaches for enhancing understanding of conceptual relationships in introductory mechanics. A reflection on the evolution of the design principles is given, resulting in the documentation of the research contribution of the study.

1.8 Research contributions

The significance of this thesis is to have explored a new approach which had not been considered before and which has resulted in some promising increased understanding of how to help students learn specific concepts and relationships associated with an understanding of motion in free fall.

There have already been a number of conference presentations, conference papers and journal articles and articles produced from this research. While the published papers and articles are specifically reproduced at relevant points in later chapters, all contributions are now listed for convenience of the reader.

Conference presentations:

1. "Investigating introductory students' conceptual understanding of physics: rephrasing the questions." Ferreira, A. & Lemmer, M. International Conference on Physics Education, **Beijing**, China, August 2015.
2. "Investigating students' conceptual understanding through solving kinematics problems in various contexts." Ferreira, A. and Lemmer, M. 11th Conference of the European Science Education Research Association, **Helsinki**, Finland, September 2015. (Later published in the conference proceedings – see Publications).
3. "Working with Variables and Relations." Lemmer, M. & Ferreira, A. 6th ISTE International Conference on Mathematics, Science and Technology Education; Mopani Camp, **Kruger National Park**, October 2015.
4. "An alternative approach to teaching the concept of acceleration." Ferreira A & Lemmer M. 2nd World Conference of Physics Education, **Sao Paulo**, Brazil, July 2016.
5. "Reflections on the process of designing and implementing a teaching sequence on Newtonian mechanics". Lombard, E. & Ferreira, A. 2nd World Conference of Physics Education, **Sao Paulo**, Brazil, July 2016.

6. “When heavy objects don’t fall faster”. Ferreira, A., Seyffert, A & Lemmer, M. 12th Conference of the European Science Education Research Association, **Dublin**, Ireland August 2017.

Publications:

1. Ferreira, A. & Lemmer, M. (2015). Investigating students’ conceptual understanding through solving kinematics problems in various contexts. (*In* J Lavonen, K Juuti, J Lampiselk:a, A Uitto & K Halh (Eds.) *Proceedings of the European Science Education Research Association Conference 2015*, 176-183).
2. Ferreira, A. Lemmer, M. & Gunstone, R.F. (2017). Alternative conceptions: Turning adversity into advantage. *Research in Science Education*. DOI 10.1007/s11165-017-9638-y
3. Ferreira, A. Seyffert, A. & Lemmer, M. (2017). Developing a graphical tool for students to understand air resistance and free fall: when heavier objects *do* fall faster. *Physics Education*. 52 (2017) 034002 (9pp)

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In Chapter 2 a review of existing literature that applies to this study is presented. The review includes literature on teaching and learning in general as well as teaching and learning of physics in particular. The chapter starts with a review on constructivist perspective and proceeds with literature concerning conceptual change and the role of epistemology of physics. The chapter concludes with a review of literature on the teaching and learning of physics.

2.2 A constructivist perspective

Despite the recognized importance of the development of conceptual understanding and the existence of a huge definitive body of empirical research on student conceptions (see four extensive reviews of this and related research in Driver & Erickson, 1983; Gilbert & Watts, 1983; Duit, 2009; Duit *et al.*, 2014), a substantial body of current research in physics education shows that for many students the development of a deep understanding of the fundamental relationships and core concepts in introductory physics, specifically in mechanics, remains difficult. A large number of physics students are unable to explain daily events from a scientific point of view (e.g. Muis & Gierus, 2014; Von Aufschnaiter & Rogge, 2015). For example, it is extremely common for students in introductory mechanics to be able to apply the equations that express Newton's law without letting go of a fundamentally incorrect Aristotelian view of the relationship between force and motion (Palmer, 2001; Kavanagh & Sneider, 2007; Duit *et al.*, 2014; Williamson *et al.*, 2016). It is crucial, however, that the fundamental scientific relationship and principles of motion and force should be conceptually understood because these Newtonian concepts in introductory mechanics courses are not only required to explain and predict everyday occurrences but are essential for laying the foundation for more advanced physics and engineering courses (Hedge & Meera, 2012; Williamson *et al.*, 2016).

2.2.1 Constructivism

This study is embedded in constructivism as learning theory, with its focus on conceptual development and with pedagogy often associated with active learning pedagogical practices (Duit & Treagust, 2003). Establishing learner ownership of knowledge enables learners to understand the knowledge in an intimate way (Duit & Treagust, 1998). In addition to acknowledging the importance of prior knowledge, Tiberghien *et al.*, (2009:2288) emphasize the importance of the situation in which the knowledge is introduced because "relations between new knowledge elements and prior elements of knowledge are constructed according to the student's overall

understanding of the situation". In considerations of the influences on the nature of understanding a student constructs, student epistemological beliefs are often ignored. However, student beliefs about the physics world, their epistemologies, are central to the major difficulties that are very commonly encountered when implementation of teaching based on constructivism is attempted. Because students construct their ideas and observations based on what they already know *and believe*, it means therefore that student beliefs are central to the frequently documented difficulty of creating student conceptual change (Halloun & Hestenes, 1985; White & Gunstone, 1989; Von Aufschnaiter & Rogge, 2015).

Many learning theories have always had one common feature: the fundamental concept of constructivism that the most significant impact on the nature of an individual's construction of a new knowledge structure is what they already know and believe (Ausubel, 1968). Researchers over the years have confirmed the Ausubelian assertion that the first principle of teaching is establishing what students already know and believe, and then building on that. This view is supported by Hewson (1982) who highlights the importance of a student's non-refutable (metaphysical) commitments as components of existing knowledge. The learning of physics, indeed the learning of anything, is a process of knowledge construction undertaken by an individual. As Driver and Oldham (1986) have pointed out, from a constructivist point of view the curriculum is seen not as a body of knowledge or skills but as the programme of activities from which such knowledge or skills can possibly be acquired or constructed. Knowledge cannot be simply transmitted to a student; it is important to identify what students already know before teaching them (Chang, 2005; Duit & Treagust, 1998) and to elaborate and/or reconstruct new knowledge from this basis. A range of opinions and concepts involved in reconstructing of new ideas is discussed in the sections that follow.

2.2.2 Conceptual understanding

For students to develop conceptual understanding requires a great deal of cognitive effort (Posner, Strike, Hewson, & Gertzog, 1982). Conceptual development can demand acquisition of new information, reorganizing existing knowledge, or discarding ideas that are no longer useful (Hewson, 1982), therefore, effective instructional strategies which explicitly address the learner's existing knowledge are needed for improvement of science education (Hewson, 1982). Different teaching models for physics education have been proposed by researchers during the previous decades (Champagne *et al.*, 1982), with an increasingly stronger focus in the last several decades on the design and implementation of teaching-learning activities that focus on the improvement of student understanding (Leach & Scott, 2002; Tiberghien *et al.*, 2009).

A pair of terms that has been commonly used in discussions on learning, that Leach (2015) has used once again, namely fine-grain size versus coarse-grain size, is used here to elaborate this point. The bulk of research on the teaching and learning of science, and physics in particular, can be described as being at a large grain size, with investigations of process or practice being considered in terms of content (Leach & Scott, 2008). Although general insights around teaching and learning physics (large grain size) are valuable, these are not sufficient. More specific knowledge about the details of teaching and learning specific content – knowledge at a finer grain size – is needed if student understanding is to be maximised (Leach & Scott, 2008). In designing subject specific teaching/learning sequences many decisions, both about content and pedagogy, which are at a *fine grain size* need to be made (Leach, 2015). For instance, while the effect of modelling everyday situations into theoretical physics situations by means of simplification, by ignoring the effect of air resistance, has been reported (Gunstone, 1987), no clarification of when the simplification would be justified or not justified has been found in the literature. As is shown later in this thesis, this deficit contributes significantly to student alternative conception about heavier objects falling faster and to the persistent conceptual difficulties students have in this topic.

In the case of physics education, an obvious example is the fact that although the concept of acceleration is one of the most-researched and reported topics of Newtonian mechanics, it remains a poorly understood concept. What is needed are well-developed, content-oriented teaching sequences containing detailed analyses of content, for example when introducing the idea of acceleration; what particular ideas are going to be presented to students, and in what order these should be done.

2.2.3 Threshold concepts

In all disciplines there are certain concepts that are critical precursors to student development of conceptual understanding in a domain of that discipline; these are usually labelled threshold concepts (Meyer & Land, 2005). Some of these concepts have proven to be exceptionally difficult to understand. Incomplete understanding of such threshold concepts is likely to have long term effects on student learning and their ability to apply their knowledge in new contexts. Conversely students who gain understanding of a threshold concept obtain “a transformed internal view of subject matter and subject landscape” (Meyer & Land, 2005:373).

A variety of threshold concepts in physics have been identified (Wilson, Åkerlind, Francis, Kirkup, McKenzie, Pearce & Sharma, 2010; Psycharis, 2016), e.g. force, acceleration and gravity. A good understanding of the force-mass-acceleration relationship as it applies to objects moving in a gravitational field is critical in providing a foundation for student knowledge of other physics

concepts, including, but not limited to, Newton's Laws, the laws of conservation of energy and momentum, and projectile motion (Williamson *et al.*, 2016).

2.2.4 Alternative conceptions

The term “alternative conception”, as used by Gunstone (1987) and Treagust (2012), is used in this thesis to describe pre-existing knowledge structures that contrast with formal physics concepts. We have known for over thirty-five years that this often experientially derived knowledge (which can be formed into kinds of knowledge systems) is extremely resistant to change, and that it is commonly in serious conflict with accepted scientific knowledge, i.e. the fundamental principles to be learned in physics classrooms (Champagne *et al.*, 1982; Duit *et al.*, 2014; Von Aufschnaiter & Rogge, 2015). Extensive research has reported on the influence of these alternative conceptions on the development of student understanding during their science instruction (see the extensive bibliography in Duit, 2009).

2.2.5 Missing conceptions

While the majority of undergraduate physics textbooks do touch on the effects of air resistance, they typically limit their discussion of this complicated concept in terms of a brief explanation regarding terminal speed (e.g. Halliday, Resnick & Walker, 2011; Giordano, 2012). Not explaining the concept of air resistance and the extent of its influence on moving bodies can result in “missing a conception”, the term used by Von Aufschnaiter and Rogge (2010:3) to enhance the concept of alternative conceptions. Missing conceptions may well be important conceptual stepping stones on the way to conceptual understanding. Von Aufschnaiter and Rogge (2015) argue that students lack any (explanatory) conceptual understanding of the science content offered, therefore, a qualitative discussion and explanation of the concept of air resistance for example, can contribute to reconciliation of student alternative conceptions of falling objects, with the scientific conception (de Obaldia, Miller, Wittel, Jaimison, & Wallis, 2016).

2.3 Conceptual change

“Conceptual change requires insight and intervention in students' reasoning”

(Planinic, 2007:222)

The discovery of student alternative conceptions (Duit *et al.*, 2014) is recognized as one of the major breakthroughs of physics education (diSessa, 2015) and the reality that students come to physics courses with preconceptions has become widely accepted in education research (Hammer, 1996). For example, Hewson (1982) proposed the use of instructional strategies based on “a model of learning as conceptual change, which explicitly addresses the learner's existing

knowledge" (p 61). Student preconceptions are associated with cognitive structures that interfere with, rather than contribute to, student development of expert scientists' cognitive structures (Hammer, 1996).

A view that challenges the alternative conception perspective by offering an alternative account of cognitive structure is the "knowledge-in-pieces" view of intuitive knowledge - known as the phenomenological primitives or p-prims perspective (diSessa, 1993). According to this view p-prims (student naïve knowledge) do not interfere with, but are essential to, development of student expertise. According to Hammer (1996) the agreement between the two perspectives, alternative conceptions and p-prims, is that the unsuitable cognitive structures, whether they are constructed by alternative conceptions or p-prims, should be substituted by the correct conception. Posner *et al.*'s (1982) model of conceptual change involves exchanging an existing conception for a more satisfactory scientifically acceptable conception. However, conceptual change involves more than just replacing one concept with another. Hewson (1982:61) extended Posner *et al.*'s model to include the construct of conceptual capture which he describes as "the process whereby a new conception is reconciled with existing conceptions". At least two types of learning are relevant in addressing student existing conceptions; routine learning, such as memorization or procedural learning, and the gradual changing of beliefs (Linder, 1992; diSessa & Sherin, 1998). The first type involves merely replacing one idea with another without contributing to understanding while the second type can result in restructuring of a concept by, for instance, relating the relationships among the concepts in a new way (diSessa & Sherin, 1998). diSessa and Sherin (1998:1158) describe conceptual change as "involving changes in 'the very concepts' at the 'core' of a conceptual system". What makes conceptual change more difficult is failure to unpack what the concepts that need to be changed really are. Such substitution can be achieved by conceptual change; that is by the development of non-scientific conceptions to become improved, "correct" concepts (Von Aufschnaiter & Rogge, 2015:209).

There also had been many attempts to try and better understand possible approaches that may improve student understanding over the last 30 years with little success. Research regarding conceptual change has been undertaken for many years. Gunstone (1992:129) describes conceptual change in terms of "recognizing, evaluating and reconstructing: the individual needs to recognize the existence and nature of their current conceptions, decides whether or not to evaluate utility and worth of these conceptions and whether or not to reconstruct these conceptions." Two main approaches towards conceptual change appear in the literature, the "replacement" view and the "transformation" view. These share the "recognizing and evaluating" features of Gunstone (1992) that student preconceptions should be brought out to be reflected on. According to the replacement view (Strike & Posner, 1992), conflict between student and

scientific frameworks leads students to become dissatisfied with their current conceptions. The core of the transformation view of conceptual change is that the conflict between student and scientific frameworks is taken to the extreme – the scientific conception completely replaces the student conception. The scientific conception is then explained and its adoption is promoted (Amin, Smith & Wiser *et al.*, 2014). The transformation view, in contrast, promotes capitalizing on student ideas and restructuring knowledge systems by progressively integrating new pieces of information into these systems (Osborne & Freyberg, 1985). I argue that of the two approaches the transformation view is founded on the constructivist perspective because it departs from students' existing knowledge and uses that as scaffolding on which to build better understanding, while replacing one concept with another, is not.

Although these different perspectives on cognitive structure and restructuring inform different instructional practices, considering even both perspectives would not be sufficient to determine an appropriate intervention (Hammer, 1996). Alternative conceptions that are not challenged become integrated into student cognitive structures (Treagust, 2012). In the highly experiential domain of mechanics, these alternative conceptions may already be well integrated before instruction; because the ways of making sense of one's world in order to control it are central to the nature of pre-instruction alternative conceptions for many. It is reasonably easy to learn something that matches or extends an existing mental model or student experience but it is very difficult to substantially change an established mental model or belief (Redish & Kuo, 2015). As a consequence, students experience difficulty in integrating new information into what they already know, and attempts to do this often result in incorrect understanding of the new concept (Treagust, 2012). A powerful way to challenge, and then often change, mental models, is establishing cognitive conflict. The use of active constructivist learning strategies such as Predict Observe Explain (POE) (White & Gunstone, 1992) (refer to section 2.3.2), for example, creates conducive opportunities for students to experience cognitive conflict and in the process confront their prior mental models. POE also allows one to investigate the conditions under which conceptions are transformed in the process of conceptual exchange.

2.3.1 Replacing or transforming student alternative conceptions?

After student alternative conceptions were discovered the initial approach towards changing these conceptions was to confront and refute those alternative conceptions with arguments or evidence with the intent of facilitating the student construction of new, more appropriate conceptions (Posner *et al.*, 1982). However, from the large body of research that now exists on alternative conceptions, it is evident that refutation of these conceptions fails to give the desired results. Different views on the implications of alternative conceptions for instruction are held. Initially the disagreement was about whether student conceptions should be replaced by the science

conception or whether student conceptions should be transformed into scientific conceptions (Amin *et al.*, 2014). Duschl *et al.* (2011) argued that exposure to new information does not automatically mean that the information is understood and integrated into student existing knowledge. Attempts to replace or amend student alternative conceptions with the acceptable conceptions via direct instruction, the “fix it” approach (Duschl *et al.*, 2011) or “replacement” approach (Driver, 1983), do not contribute to the reorganization and restructuring of knowledge which is required for conceptual change. Today it is argued that to address student alternative conceptions, a multiple conceptual change view that includes conceptual changes on the fundamental level of concepts and principles will be required (Duit *et al.*, 2014).

Whether existing concepts will merely be replaced by new concepts as rote-learned facts, i.e. viewed as only another version of rote knowledge, replaced and accepted through a process of conceptual exchange, or accepted through conceptual capture, the process of reconciling new conceptions with existing conceptions, depends on the linkages between the old and new knowledge (Hewson, 1982). Hewson (1982:84) states that “rote memorization places no demands on the relationship between conceptions, whereas both conceptual capture and conceptual exchange do”. (Hewson, 1982:84)

In contrast with the replacement approach, the intuition-based “work with it” view (Duschl *et al.*, 2011) uses student intuitive ideas or perspectives as starting points to design more effective instruction. This view corresponds with Hewson’s (1982) view of conceptual capture and with the transformation view, a view that “promoted capitalising on student ideas rather than confronting them and restructuring knowledge systems by progressively integrating new pieces of information into them” (Osborne & Freyberg, 1985). Gravity, for example, is a concept with which everyone has daily experience and which is therefore an excellent starting point for identifying and reshaping student alternative conceptions (Williamson *et al.*, 2016). While many students give the Newtonian response that objects under the influence of gravity only move with equal (gravitational) acceleration for vertically downward motion, the persistence of the alternative conception that heavier objects fall faster is revealed in responses to problems of motion upwards, against gravity (Lemmer, 2013; Ferreira & Lemmer, 2016). With the “work with it” view students are asked to evaluate and refine their alternative ideas in order to be aligned with the scientifically correct conceptions. Such refinements can contribute to student development of epistemological understanding. The connection between epistemological sophistication and conceptual change has been established by a convincing body of research (Duit, 2009; Amin *et al.*, 2014). Therefore, a new reason for developing epistemological understanding has emerged, namely to promote conceptual understanding itself (White & Gunstone, 1992; Amin *et al.*, 2014).

The “work with it” view aligns with the account Amin *et al.* (2014:64) gives on how conceptual change is promoted by “encouraging students to reflect on their alternative ideas, develop shared norms and epistemological standards to discuss and evaluate their ideas, and work to solve anomalies or inconsistencies between alternative and scientific conceptions by restructuring a network of concepts”. This can be illustrated by reference to Elby pairs; a term used for questions in which students are asked to answer two related questions (Hammer & Elby, 2003). Here a teacher can recognise student inconsistent reasoning from responses to Elby pairs, and so help students to reflect on their alternative responses and discuss with them the responses to paired questions in instruction-assisted interventions. This is the creation of *teachable moments* to help students reconcile the two responses. When students recognize how their alternative ideas need to be refined in order to be aligned with the scientifically correct conceptions, new levels of explanation are achieved (Duschl *et al.*, 2011).

Although cognitive and affective issues are closely linked in conceptual change (Gunstone, 1992; Duit & Treagust, 2003; Amin *et al.*, 2014), the nature of this present research did not allow inclusion of the affective measures that may be involved in conceptual change. However, I note here that exclusion of such aspects does not indicate their unimportance.

2.3.2 Predict Observe Explain as strategy to achieve conceptual change

“Instruction should, amongst other things, be directed at lowering the status of undesirable conceptions (thereby requiring that they be known) and raising the status of desirable conceptions (which often can occur only at the expense of existing conceptions)”.

(Hewson, 1982:66)

A primary task for encouraging conceptual change would be to replace, or at least weaken, student alternative conceptions. To achieve that, the alternative conceptions should be identified before these can be confronted. A well-known and widely used way to get students to identify their own alternative conceptions is the Predict-Observe-Explain protocol (POE) developed by White and Gunstone (1992). This procedure is a good probe of the ability to apply knowledge. It requires that students decide what reasoning to use, to decide what knowledge is relevant and, possibly, to reconsider their understanding in the light of an observation that is different from their prediction. POEs reveal much about the understanding of the particular concept(s) that is/are central to the situation. The POE is often implemented to indicate student ability to apply knowledge by asking them to predict the outcome of a specific event; this, through the nature of the justifications given in support of the prediction, can reveal much about the understanding of single bits (“elements”) of knowledge (Gunstone, 2016). Requiring a prediction makes it more likely that the knowledge the student believes to be most important will be applied (White &

Gunstone, 1992; Miller, Lasry, Chu & Mazur, 2013). POEs are highly valuable for the teaching of science. In one sense these are a restructuring of standard demonstrations, with the restructuring resulting in greater thinking by most students about the “demonstration” and a much higher chance that students will be focussed on the “demonstration”. The POE creates in most students a powerful “need to know” that results in a strong observational focus on the aspect of the “demonstration” that is important to the teacher and a greater chance of the “demonstration” being integrated into the understanding of the student (White & Gunstone, 1992).

When student observations are in direct contrast with what they predicted, then often their understanding of the particular concept is probed which in turn often creates cognitive conflict (Johnson & Johnson, 2009; Von Aufschnaiter & Rogge, 2015). (In some contexts it is instead the observation that is challenged when it conflicts with the prediction [Gunstone & White, 1981]). Attempts to accommodate or, better, assimilate this cognitive conflict often create possibilities for teachable moments - instruction-assisted development of learning. When students are encouraged to resolve the cognitive conflict they will be more likely to learn to think about coherence and use reasoning to evaluate and refine their intuitions (Gunstone, 2016). Teachable moments in some ways rely on a fine grained approach because these moments are very specific to a particular point in the sequence of the content or a specific aspect of the conceptions that students bring to the classroom. Miller *et al.* (2013:4) support the “importance of having students predict the outcome of an event, regardless of whether they predict correctly or not”, and the consequent effectiveness of the POE protocol towards development of conceptual understanding.

2.3.3 The inability of conventional teaching to generate conceptual change

The large body of research on alternative conceptions frequently reports on the difficulties these conceptions cause in learning (Driver & Erickson, 1983; Gilbert & Watts, 1983; Duit, 2009; Duit, *et al.*, 2014). Students do not alter their beliefs easily and teacher-telling certainly does not result in student conceptual change. Having a belief that heavier objects always fall faster does not change when a teacher says it is wrong. Conceptual change requires at least reconsideration of the existing belief and comparing its value and accuracy against the new information (White & Gunstone, 1989; Halloun & Hestenes, 1985; Planinic, 2007). Research on student epistemology indicates that students are motivated to develop reasoning skills when they realize their beliefs are inhibiting their progress, i.e., acknowledging that they need to balance competing and conflicting cognitive frameworks (Champagne *et al.*, 1982; Planinic, 2007).

Physics education research shows that teachers often fail to facilitate student understanding of physics concepts (Champagne *et al.*, 1982; Duit, 2009; Halloun & Hestenes, 1985; McDermott & Shaffer, 1992; Von Aufschnaiter & Rogge, 2015). Consequently, student knowledge of physics

concepts is relative to how familiar to them is the problem they are trying to solve (Concannon, 2012). The common school focus on one-dimensional motion alienates high school physics from the everyday life experiences of the students. Students are reported to learn the sets of routine manipulative rules associated with acceleration, for example, without understanding the essence of the concept acceleration (McDermott, 1984, Basson, 2002). Traditionally, physics education research has been content-specific; evaluating student knowledge about a specific topic (Osborne & Freyberg, 1985). Student capability to give Newtonian responses without Newtonian reasoning in regularly used multiple choice questions, however, leads to overestimation of the level of correct knowledge revealed by such questions and an often unwarranted assumption of conceptual understanding of concepts (Palmer, 2001). Student poor performance on problems set in real world contexts highlights conventional instruction's failure to identify, let alone address, ineffective tuition practices (Gunstone & White, 1981; McDermott, 1984; Von Aufschnaiter & Rogge, 2015) and the consequent need to develop tools that differentiate between student content knowledge and conceptual understanding (Rebello & Rebello, 2013; Muis & Gierus, 2014).

The majority of teachers do not effectively diagnose student learning problems (Treagust, 1995). Although various formative and summative assessment methods to obtain information on student learning are available, most of the methods are time consuming and consequently impractical for teachers to use (Treagust, 1995). However, when obstacles in the way of student understanding are identified and more effective instruction, informed by understanding the nature and content of student conceptions and the process of conceptual change, is designed (Amin *et al.*, 2014), student learning needs can be addressed by incorporating specifically designed instruction procedures consistent with constructivist teaching approaches (Treagust, 1995; Amin *et al.*, 2014).

Teacher failure to facilitate student understanding may be a consequential result of the "epistemological overtones they (teachers) reflect on their students" (Linder, 1992:111). Teachers need to consider what implicit messages they send to students by the way they approach their teaching. Linder (1992) highlighted four hidden messages that discourage students' development of conceptual understanding. If teachers see teaching as teacher-to-student transfer of proven knowledge and algorithmic routines (p.112) time spent on discussions for conceptual understanding will be considered as wasted time, hence encouraging rote-learning. The successful solving of standard sets of physics problems is often incorrectly assumed to indicate conceptual understanding. A related incorrect linkage is also drawn between "incorrect understanding" and "not working hard" (p. 117). Finally, by not allowing or facilitating discussions where students share their understanding of knowledge, development of conceptual

understanding is not encouraged. The failure to include assessment of conceptual understanding in end-of-the-year examinations largely contribute to prevailing ineffective teaching approaches.

In addition to ineffective teaching practices, discrepancy in teaching physics occur for promoting conceptual understanding whilst harbouring unjustified assumptions regarding the level of complex content that 'immature' students are capable of understanding (Galili, 2001). Total exclusion of ideas such as 'relativistic' and 'quantum' based on their formal complexity, cannot be justified. Topics that can enrich the physics curriculum for example, 'relativistic' and 'quantum' are excluded because of their assumed formal complexities while other advanced topics are simplified to make the course more attractive to students (Galili, 2001:1088).

2.4 An epistemological perspective

In this section I review literature that is relevant to the ways that the nature of student knowledge interacts with student physics knowledge. Two issues that revealed itself are physics as a body of knowledge and its relationship to mathematics and student perception of it.

2.4.1 Student epistemologies

Student perceptions of the nature of physics knowledge (i.e. their epistemologies of physics) affect many aspects of their physics learning, including their reasoning about physical situations (Chu *et al.*, 2008; Duit *et al.*, 2014; Muis & Gierus, 2014; Von Aufschnaiter & Rogge, 2015), and the extent to which they are willing to recognize, evaluate and reconstruct those ideas (Gunstone, 1992). For example, students who think that science knowledge consists of unrelated, static and unchangeable facts may find it difficult to obtain a coherent view of physics as an interrelated web of concepts and relationships (Amin *et al.*, 2014; Duit *et al.*, 2014; Ledermann & Ledermann, 2014). Every student in introductory physics has a system of beliefs about physics, mostly developed unconsciously and based on their everyday-life observations and experiences and their beliefs about physics (examples of reviews of relevant research are found in Duit *et al.*, 2014; Ledermann & Ledermann, 2014). Physics education research worldwide has pointed to many conceptual difficulties that students have when learning physics, most particularly for alternative conceptions relevant to the domain of mechanics. Many studies have reported that student conceptual development is related to both their cognitive understanding of individual physics concepts and their epistemological beliefs about physics (e.g. Chu *et al.*, 2008; Chu & Treagust, 2014; Duit *et al.*, 2014). Student epistemological frameworks vary from beliefs that knowledge consists of incontrovertible absolute truths - i.e. isolated facts that are fixed - to sophisticated beliefs that knowledge is subject to change, consists of coherent, interrelated ideas and involves the invention of explanations (Amin *et al.*, 2014; Ledermann & Ledermann, 2014).

2.4.2 Coherence of physics concepts

Physics is based on a small number of concepts and their interrelationships which are the foundation for various applications (van Heuvelen, 1991; Duschl *et al.*, 2011). Some student perceptions of physics as a set of disconnected facts and formulae, and of physics learning as absorption of information, contribute to their difficulty to apply concepts and principles to explain phenomena and solve problems to make sense of the natural world (Ledermann & Ledermann, 2014). Responses like “it is common sense”; “according to Galileo”; “the textbook states”; “experts say that” point towards a naïve, unsophisticated physics framework, founded on external authority.

Students who emphasize science as a collection of facts fail to see the coherence of the structure of physics knowledge (Redish, Saul, & Steinberg, 1998) and this lack of perceived coherence is among the principal causes of student failure to achieve conceptual understanding in physics (Champagne *et al.*, 1982). Ideally, students should see physics knowledge in terms of the fundamental physics concepts tied together as a coherent web of ideas, and where learning involves relating fundamental concepts in this web as they build their own understanding (Elby, 1999; Ogilvie, 2009). When students conceptually understand the underlying physics concepts, and when they know where and when specific concepts and relationships apply, their ability to solve problems, to see physics knowledge as a coherent web of ideas which applies to all walks of life, and to predict and explain various phenomena scientifically is enhanced (Amin *et al.*, 2014; Muis & Gierus, 2014).

2.4.3 The importance of context

Knowledge is constructed within a certain contextual setting. What is learned tends to be context-bound or tied to the situation in which it is learned (Lave & Wenger, 1991; Gilbert, 2006; Ferreira & Lemmer, 2016, Ferreira, Lemmer & Gunstone, 2017). A good example of this is apprenticeship, often a most helpful way to learn, which is always contextually embedded. Situated learning, also termed situated cognition, refers to learning that only makes sense when it is situated in context. However, in most cases that is exactly what physics teachers do not do. Although contextual learning facilitates student understanding of physics concepts, the central problem that describes most physics teaching is that teachers often focus almost exclusively on knowing to solve simple standard physics problems, i.e. rote application of a mathematical formula, as opposed to a focus on student understanding (Concannon, 2012).

The context in which learning occurs is an integral part of what is learned. Studies of the effects of problem-context have evolved to allow evaluation of student concept development and their

level of conceptual understanding (Stewart, Griffin & Stewart, 2007). A concept inventory is a kind of research-based assessment instrument that probes student understanding of particular concepts (Madsen, McKagan, & Sayre, 2014). The Force Concept Inventory (FCI) (Hestenes, Wells & Swackhamer, 1992) is probably the most commonly used concept inventory in physics education. Concept inventories have many affordances; in particular, they allow one to make comparisons of the effectiveness of one's teaching and comparison of conceptual understanding between students in different classes and universities (Madsen *et al.*, 2014). By comparing the way in which students apply the same physics concept in different contexts, for example, inconsistencies in their reasoning are revealed. Concept inventory questions usually require deeper understanding, meaning considering "the contextual character of conceptions and clarifying the empirical relationships" between them (Svensson, 1989), and therefore students find them often more difficult than typical end-of-chapter problems. When differences between student naïve knowledge and the relevant physics concept can be identified before and/or during instruction, these differences can be addressed immediately to help students see the coherence of fundamental physics concepts (Minstrell, 1982; Ogilvie, 2009).

There are excellent reasons relating to student learning for the very common simplification of the content structure to be the focus of physics instruction, but this must also be enriched by embedding the structure in contexts that make sense for the students. Evidence for the situational nature of learning of physics knowledge can be seen in numerous cases where student school learning fails to transfer readily to relevant tasks outside of school. For instance, Brown, Collins and Duguid (1989) describe how people can apply relatively sophisticated mathematical operations in one setting and yet be quite unable to apply the same operations in another setting. For an example in physics, consider how many students know the Newtonian simplification that objects released from the same height at the same time experience equal acceleration as they fall (in the absence of air resistance) and therefore will reach the ground at the same time. Yet when students have to apply the same concept (i.e. free fall) for the objects projected upward against gravity and for motion along an inclined plane — still all linear motion and so in terms of physics principles the same motion — they are unable to do so correctly (Palmer, 2001; Lemmer, 2013; Ferreira & Lemmer, 2016).

Evidence of the context dependence of student alternative beliefs highlights the vital role that context plays in the physics learning process (Gunstone & White, 1981; Muis & Gierus, 2014; Ferreira & Lemmer, 2016). Student reasoning varies in accordance with their epistemological framing of the situation or their general beliefs about how a physics problem should be addressed (Stewart *et al.*, 2007; Muis & Gierus, 2014). For example, when confronted by contextual problems - that is, problems embedded in an everyday context - most students rely on their pre-

instruction epistemic beliefs; this is a problem because those beliefs, based on their experiences, do not take into account that the “physics” situation is a simplified version of the contextual problem. This will very likely mean that specific patterns in student reasoning are activated by the context of problems (Hedge & Meera, 2012; Rebello & Rebello, 2013; Amin *et al.*, 2014). While the context of problems activates various patterns in student reasoning, distinctive characteristics of the context cue the recalling of specific information that either promotes or discourages understanding of physics concepts (Elby & Hammer, 2010; Ferreira, Lemmer *et al.*, 2017). Distinctive characteristics of words used in the problem statement, i.e. surface features such as ‘inclined plane’, often cue the recalling of specific thinking that inhibits understanding of physics concepts. Novice students are much more likely to identify such surface features of a problem situation while, in contrast, experts treat the surface features as irrelevant and focus on the fundamental principle(s) not always specifically mentioned in the problem statement involved, i.e. the deep structure of a physics problem (Champagne *et al.*, 1982; Serway & Vuille, 2014).

2.4.4 The relationship between physics and mathematics

The high level of conceptual abstraction and the predominant role of mathematics which distinguish physics from much of the other natural sciences may be responsible for certain teaching and learning difficulties (Duit *et al.*, 2014). However, Hewitt (1983) criticizes the mathematical perspective on physics. Instead of viewing physics as an applied mathematics domain, he sees physics as “being so simple it can be easily expressed in mathematical form” (Hewitt, 1983:305). Physics is based on a relatively small number of fundamental principles and concepts, many of which are meaningfully condensed in mathematical equations (Duschl *et al.*, 2011; Singh, 2007; Van Heuvelen, 1991). Unfortunately, “good performance” in physics is commonly associated with routine problem solving, using physics formulas and mathematics. However, research comparing student performance on algorithmic versus conceptual problems has consistently reported that the ability to solve large numbers of numeric problems does not facilitate student conceptual understanding. Consequently, there seems to be little correlation between the number of numeric/algorithmic problems solved and the development of conceptual understanding (Kim & Pak, 2002). The road to deep understanding of mathematical models in physics is complex and should be a major concern in physics teaching and physics learning research (Mäntylä & Hämäläinen, 2015). The mathematization of physical systems does not merely entail transfer of mathematical techniques to the physical environment, but also, and more importantly, the merging of mathematical symbols and reasoning with physical meaning (Redish & Kuo, 2015). It is enhanced by interpretation of mathematical models (which represent the relationships between physics variables) in the physical systems that are validated in reality (Redish & Kuo, 2015). Many teachers however, err in a critically important way in making the

assumption that because it is easy to teach physics mathematically, it is also easy to learn physics mathematically (Hewitt, 1983). He advocates a conceptual approach to teaching physics; “a qualitative study of the central concepts of physics with emphasis on mental imagery that relates to things and events that are familiar in the everyday environment” (Hewitt, 1983:305).

Because real world phenomena are influenced by multiple and complex variables which require advanced physics for prediction and mathematics for measurement of those phenomena, the knowledge to be taught is often simplified, by disregarding certain disciplinary aspects, for physics teaching. Empirical studies all over the world have reported and confirmed student conflicting ideas on force and motion to such an extent that these ideas are referred to as the “body of intuitive mechanics” (Duit *et al.*, 2014:446). The conceptual vocabulary needed to explain physical phenomena is impoverished by student poor comprehension of the basic concepts and relationships contained in physics representations such as equations (Halloun & Hestenes, 1985). Student ability to develop their conceptual understanding is inhibited by imprecise definition of the terminology for physics concepts and quantities, and their attributing meanings to concepts that differ from meanings generally used by physicists (Gunstone & White, 1981; Champagne *et al.*, 1982). Various physical phenomena can be explained if these principles are unpacked appropriately and their application in different comparable contexts understood (Singh, 2007; Krajcik & McNeill, 2015). Failure to correctly interpret the meaning and the attributes of the variables contained in physics equations, for example, inhibits the development of conceptual understanding of these core concepts. As a consequence, conceptual understanding of concepts that are founded on any of these core concepts will also not be developed.

2.4.5 Proportional reasoning

Proportional reasoning, a form of mathematical reasoning, is a fundamental connection between science and mathematics (Heller, Ahlgren, Post, Behr & Lesh, 1989). Although many relationships in physics are proportionalities represented by an equation of the form $y = kx$, students have great difficulties solving problems that involve proportional reasoning (Heller *et al.*, 1989; Akatugba & Wallace, 1999). Not enough attention has been given to student use of the mathematical aspects of proportional reasoning in terms of the subject-specific context of physics (Akatugba & Wallace, 1999). As most proportional reasoning in physics concerns ratios, Heller *et al.* (1989) suggest that teachers should question both student ability to reason qualitatively about ratios and the adequacy of mathematics instruction to teach proportional reasoning in a way which is useful to the learning of science. Fleener (1993, as cited in Akatugba & Wallace, 1999:37) asserted that “most instruction tends to treat proportional reasoning as a skill to be mastered rather than a general reasoning construct”. According to Akatugba and Wallace (1999) there is a need to determine how qualitative reasoning about ratios contributes to proportional reasoning skills.

2.4.6 Use of equations in physics

It is important that students understand that equations are used to describe the relationships between physical quantities. However, many introductory-level students equate learning physics with finding formulas and problem solving algorithms (Elby, 1999; Ogilvie, 2009). Equation hunting for the 'correct' formula promotes rote learning; this in turn affects problem solving ability and causes students to disregard the concept features of a problem (Hedge & Meera, 2012) and so is a significant aspect of the common novice focus on 'surface' features of a problem discussed above (see Section 2.5.2). It is reported that students apply mathematical algorithms and proportional reasoning patterns (including in physics) without being able to explain the mathematical procedures underpinning the algorithms. Hewitt (1983) argues for a conceptual approach to introducing physics concepts - to teach the basic principle instead of teaching the mathematics. Furthermore, students are often unable to explain why they apply a specific algorithm in physics problem solving because they find it difficult to translate physics tasks into mathematical relations (Akatugba & Wallace, 1999). Student weakness in connecting the symbols in equations to the physical quantities the equations represent can be an indication that they tend to look at equations in physics as mathematical executions instead of as representations of relationships between physical quantities (Redish, 2006; Hedge & Meera, 2012). Many introductory students often do not understand the conditions under which equations are applicable and what restrictions exist for these applications. Consequently, the use of physics equations as reasoning tools, in addition to the mathematical use thereof, remain hidden from students.

When considering the underlying concept that is represented by a mathematical equation, students build up and organize knowledge as a network of connected knowledge elements, ideas, and relationships (Leonard, Gerace, & Dufresne, 1999; Schuster & Undreiu, 2009). Qualitative reasoning, a factor that figures to a great extent in mathematics and physics problem-solving, is a skill that expert problem solvers are likely to apply before proceeding to quantitative reasoning which is sadly neglected in school and undergraduate physics teaching (Champagne *et al.*, 1982; Heller *et al.*, 1989). The use of qualitative problem solving strategies may greatly benefit both students and instructors (Leonard *et al.*, 1999). Possible reasons for student lack of qualitative reasoning abilities include student difficulty in representing the physics tasks in meaningful mathematical proportional statements and mathematical symbols, and a lack of understanding the meaning of basic quantities and concepts in physics representations (Champagne *et al.*, 1982; Finegold & Gorsky, 1991; Van Heuvelen, 1991; Akatugba & Wallace, 1999).

2.4.7 Equations and relationships as reasoning tools

In the data chapters of this thesis, in particular Chapters 5 and 7, the concept of proportional reasoning has been used in a slightly different way than is described in the previous paragraphs. In these data chapters I have used the term 'proportional reasoning' in a broader sense, to introduce the use of physics equations as qualitative reasoning tools to compare and make a prediction on the motion of two comparable situations. Instead of focusing on ratios and translating verbal representations of two comparable situations into mathematical representations, a physics equation has been written for each one of the two comparable situations for which one physics quantity differed. By comparing each one of the variables for one situation with the corresponding variable for the other situation, the effect of the physics quantity that differed can be inferred. The extent to which this comparative proportional reasoning approach explains and simplifies the qualitative use of physics equations is a topic for research stemming from this thesis. Non-quantitative connections as represented by physics equations and other aspects of the physical situation are critical in developing understanding of the relatedness of physics quantities (diSessa & Sherin, 1998). The worth of qualitative use of equations is highlighted by diSessa and Sherin (1998:1178): 'Qualitative interpretations of equations are more important than precise calculation in equations' role in coordination'. This notion of qualitative reasoning with equations has been explored in the iterations of this research.

2.5 Learning physics

2.5.1 Conceptualisations of acceleration

The concept of acceleration is one of the threshold concepts identified for introductory physics (see section 2.2.3). Two different approaches to the teaching of acceleration are discussed below.

2.5.1.1 The traditional mathematical conceptualisation

Students struggle with the understanding of the concept of acceleration, from the introduction thereof to postgraduate physics years (Taşar, 2010; Lemmer, 2013). Content analysis of the Curriculum and Assessment Policy Statement (CAPS) for Physical Sciences and a selection of prescribed textbooks for grades 10 – 12 in South Africa (the location of this research) revealed that the concept of acceleration is always introduced from a kinematic perspective; that is from a time derivative of velocity approach. Traditionally in classrooms in this country the sequence is developed from the basis of velocity being the change in displacement per time unit. This approach is then usually followed by the modes of disciplinary discourse (Airey & Linder, 2009), for example, words, pictures, graphs, equations, that lead towards the introduction of acceleration. To appreciate the formal definition of acceleration as the time derivative of velocity

requires an understanding of both derivatives and of velocity, including its vector character. Both aspects have been found to be problematic at school and also for undergraduate university physics students (Taşar, 2010). Students often tend to forget the vector nature of velocity and acceleration; hence the case of acceleration as a rate of change of *direction* of the velocity is often not considered in a simplified treatment where motion is studied only in one dimension. Restricting discussions of acceleration to one-dimensional motion and to situations where a body starts from rest excludes many applications of everyday experience of acceleration, and thus may well restrict understanding of the concept of acceleration that is flexible and useful in solving real problems.

A focus on acceleration as the result of the net effect of [a] force/s acting on a body (a ‘dynamics’ focus), rather than a focus on uniform, rectilinear motion (a ‘kinematics’ focus), offers different qualitative ways of understanding the concept of acceleration. An example of such an alternative way to introduce acceleration, in terms of 3-dimensions, was suggested by Pendrill (2008). She introduced 10 – 11 year olds to different rides in an amusement park to experience both a body in motion and measurement within this moving system. She claims that introducing acceleration in one-dimension (and neglecting air resistance) could create further alternative conceptions. For example, when a ball is thrown into the air, students often indicate that the acceleration is zero where the ball is changing direction, an idea that relates to the view of Buridan, a scientist in the 14th Century (Osborne & Freyberg, 1985). It is possible that the “zero acceleration at the top” could be the result of students failing to understand that velocity and acceleration are vectors and acceleration is the time derivative of velocity, or it can be due to students not understanding the force-acceleration relationship (McDermott, 1984; Osborne & Freyberg, 1985).

2.5.1.2. A conceptual conceptualisation: Acceleration as the force to mass ratio

In addition to acceleration being introduced mathematically as the rate of change in velocity, it can also be modelled as the net force-to-mass ratio. In this approach acceleration is considered from a dynamics perspective: as the result of the interaction of forces on bodies. The notion that “forces are the cause of motion” can easily be misinterpreted as implicating impetus forces, therefore I chose to use the term “interaction of forces on bodies” to mean forces as the *cause of changes* in motion of bodies. An argument can be made to approach acceleration from the perspective of dynamics as “forces as the causes of change in motion” perspective. This is a conceptual approach that precedes introducing the abstract velocity-time approach, which requires mathematization of physics concepts before conceptual understanding is established (Ferreira & Lemmer, 2016; Ferreira, Lemmer *et al.*, 2017). The relationship between force, mass and acceleration, known as Newton’s second law and represented mathematically as $\Sigma \mathbf{F} = m\mathbf{a}$, is probably the best known equation in school physics. Wilson *et al.* (2010) report that students

who could apply the mathematical expression of Newton's second law still embraced a fundamentally Aristotelian view of the relationship between force and motion.

Introducing the force-mass-acceleration relationship as a mathematical relationship is in principle no different from the traditional kinematic approach used to introduce acceleration. However, instead of representing Newton's second law in the format of $\Sigma \mathbf{F} = m\mathbf{a}$, I argue here for the alternative representation of the law as $\mathbf{a} = \frac{\Sigma \mathbf{F}}{m}$, a format also used by Redish (2014:538; 2017:5).

In this format the equation is aligned with the definition of Newton's second law, namely: *When a net force is acting on an object the object will accelerate in the direction of the net force. The [magnitude of] acceleration is directly proportional to the net force and inversely proportional to the mass of the object.* In addition to the benefit of relating the verbal representation of Newton's second law directly to the mathematical expression of the law, it also provides the opportunity to emphasize the proportional relationships that are represented by physics equations. While students find it easy to define acceleration in terms of the equation $\Sigma \mathbf{F} = m\mathbf{a}$, and can solve numerous simple problems by plugging values into the equation, they struggle to transfer this quite superficial understanding to unfamiliar contexts (Trowbridge & Mc Dermott, 1981). For example, when interpreting Newton's second law as a mathematics equation in the format of $\Sigma \mathbf{F} = m\mathbf{a}$, many students fail to recognise that the two quantities, force and acceleration, are conceptually different. Many students do not recognize acceleration as the result of a net force acting on an object and then, according to Freedman (1996:310), "students frequently make reference to such chimera as 'the force due to acceleration' or 'the force due to momentum'." The approach that Pendrill (2008) and Ferreira and Lemmer (2016) argue for, to change the formulation of Newton's second law to $\mathbf{a} = \frac{\Sigma \mathbf{F}}{m}$, shifts the focus from force to acceleration. Understanding how to interpret and use proportionalities represented by the equation is a prerequisite for conceptual understanding before presenting the relationships in a mathematical form. This supports my argument that physics concepts should be introduced from a conceptual approach – as is done in this study with acceleration.

2.5.2 Alternative conceptions important for this study: F_{net} and air resistance

2.5.2.1. Alternative conceptions regarding Newton's laws of motion

As discussed in Section 2.2, the most extensive learning research over many years in introductory physics has been done in the domain of mechanics. Whether viewed from the perspective of p-prims (diSessa, 2015) or the perspective of alternative conceptions, researchers are united in that no p-prims or alternative conceptions are as robust and complicated and comprehensive as those associated with Newton's laws (Hammer, 1996). An example of an alternative conception can be

taken from a common consequence of the traditional approach to instruction of Newton's first law. When first taught about inertial motion for example, students often have difficulty understanding this interpretation, due, to their existing alternative conceptions about forces and motion (Hammer, 1996). Their experience that objects stop moving when one stops pushing them is seen to conflict with what they are taught through Newton's laws of motion. This conflict sometimes causes students to modify Newton's first law into a description that fits their experience within their understanding, and to state that "An object stays at rest unless a force acts on it," omitting the 'offending' concept that an object in motion will continue its motion unless a force acts on it (Ferreira, Seyffert & Lemmer, 2017). This modification, while more easily reconciled with their experience, effectively negates their tuition since they still do not understand Newton's first law. The laws of motion are traditionally introduced through non-motion, discussing forces on a system at rest. The study of forces then traditionally moves on to equilibrium situations, where all forces balance. If the body is *not* at rest, it thus remains in uniform rectilinear motion and Newton's first law can seem to contradict everyday experiences such as a cyclist needing to pedal to keep going and a car coming to rest unless the engine continues to provide energy (Ferreira, Seyffert *et al.*, 2017).

2.5.2.2. Alternative conceptions regarding free fall

One of the most reported alternative conceptions in introductory mechanics is that 'heavier objects fall faster', which conflicts with the Galilean principle of free fall. While it is clearly observed that, if they fall far enough, heavier objects do indeed fall faster, the complications here include that for some students their observed experience counters the physics assertion of equal times of fall for objects (i.e. equal accelerations) in a uniform gravitational field. The knowledge students gain through experience is often transformed into intuitive rules and explicit conceptions (Amin *et al.*, 2014; Von Aufschnaiter & Rogge, 2015). The resulting knowledge structure is commonly very stable, and activated by the student in a wide variety of contexts. Ferreira and Lemmer (2016) report inconsistencies in student understanding of the force-mass-acceleration relationship as, while students tended to choose the Newtonian concept of equal gravitational acceleration for objects in vertical downward free fall, they reverted to their alternative conception that heavier objects fall faster for vertical upward motion i.e. motion against gravity. Student understanding of gravity is closely related to their understanding of other physical concepts (Williamson & Willoughby, 2012) and the concept of gravitational acceleration is applied within a range of mechanic topics such as projectile motion (in one- and two-dimensions), Newton's Laws, conservation of energy, and conservation of momentum (Williamson *et al.*, 2016). Understanding the relationship between gravity and acceleration is therefore critical in building a foundation for more advanced physics knowledge.

Alternative ideas (alternative conceptions) about acceleration cause learning difficulties and frequently continue to be held even after instruction, especially when students perceive a principle taught in their physics class as being in conflict with their experience (Champagne *et al*, 1982; diSessa, 1982; Halloun & Hestenes, 1985). An important instance of this occurs when students are instructed to ignore the effect of air resistance – when solving kinematics problems because their everyday experience (the existence of air resistance) is in contrast with the idealized physics situation (the absence of air resistance). Notions such as ‘a bigger weight will cause a bigger acceleration’, ‘gravity exerts the same force on all objects no matter what their weight’ and ‘heavier objects fall faster’, have been widely reported for over many years (see two extensive reviews of this and related research in Driver and Erickson, 1983; Gilbert and Watts, 1983). The concept of air resistance and the effect thereof on falling bodies is discussed in Section 2.5.2.3 as well as in Section 2.6.3.6, with both sections concerned with aspects of free falling bodies.

2.5.2.3. The “missing conception” of air resistance

Aerodynamics is one of the more advanced topics in physics. This is very likely why information on and explanations of the effect of air resistance on projectile motion (the motion of objects moving freely through the air) in introductory undergraduate physics textbooks is limited. Ideal projectile motion is motion in which the gravitational force is assumed to be the only force acting on a projectile. Real projectiles however, also experience a force due to air resistance (Elert, 2013). In some cases, this force due to air resistance can have a significant effect on the projectile’s motion, while in other cases the effect of air resistance can justifiably be ignored.

Careful analysis of eight different South African grades 10 – 12 high school Physical Sciences textbooks revealed that the physics of falling objects is primarily discussed in terms of the Galilean principle of free fall, ignoring the effects of air resistance. The net effect of gravitational force and air resistance is discussed in just two of the eight school textbooks, and then only briefly. While the majority of undergraduate physics textbooks do touch on the effects of air resistance, they typically limit their discussion thereof to a brief explanation of the concept of terminal speed (e.g. Halliday *et al.*, 2011; Giordano, 2012). I argue that not explaining the concept of air resistance and the extent of its influence on moving bodies results in “missing a conception”, the term used by Von Aufschnaiter and Rogge (2010:3) to enhance the concept of alternative conceptions. Missing conceptions may well be important conceptual stepping stones on the way to conceptual understanding. Von Aufschnaiter and Rogge (2015) argue that students lack any (explanatory) conceptual understanding of the science content offered.

A predictable consequence of this focus on ‘pure’ free fall in undergraduate tuition is that the majority of mechanics problems students are asked to solve are accompanied by statements like

“ignoring air resistance.” Physics problems accompanied by such statements, however, rarely serve their intended purpose of aiding the student in developing an acceptable conception of Newtonian mechanics. Since air resistance plays a significant role in many phenomena students encounter in their daily lives, statements like “ignoring air resistance” serve only to further disconnect what they are being taught from their everyday experience. Discussions on and usage of alternative conceptions are crucially important in creating meaningful learning; learning “seen to be of worth, of real purpose, in a wide variety of contexts” (Gunstone, 2015:625) in the pursuit of conceptual understanding.

2.6 Pedagogic framework on teaching acceleration and related concepts

2.6.1 Modelling real world situations into physics situations

Describing the physics involved in real world phenomena is extremely complex. Real world physics involves multiple and complex variables which in turn requires advanced physics for prediction about, and often advanced mathematics for measurement of, those phenomena. Hence, some of the disciplinary aspects are deliberately ignored so that it is easier to notice other more critical aspects, the core underlying physics concepts. There is a number of physics concepts which, when introduced in introductory physics, are presented in terms of a closed system, for example the conservation of energy and of momentum, and Newton’s first and second laws. This is almost always done by including “conditional” statements in the definitions or descriptions of such concepts and relationships to control or lessen the variables that actually apply to the situation. However, such conditions (if not explained, or sometimes even when explanations are given) often do not simplify the content but instead complicate the situations for students and so add to the perceived (and actual) difficulty of physics (Gunstone, 1987).

2.6.2 Conditions contained in physics laws and definitions

Physics laws and definitions taught in introductory mechanics contain conditional statements attempting either to clarify the circumstances for which the law or definition would be true, or to simplify the physics that describes a particular everyday situation. Successful interpretation of conditional statements embodied by words such as *and*, *if*, *or*, requires genuine understanding in reasoning about logical propositions (Piburn, 1990). Teachers are often unaware of the logical operations implied by such statements especially when a definition or law is regarded as something that has to be ‘known’ rather than understood. In Newton’s first law of motion, for example, the conditional statement is preceded with the word *unless* e.g. an object will maintain its state of rest or constant velocity *unless* unbalanced forces act upon it. Phrases such as “in a closed system” or the usage of words like “if”, “unless”, “if then” usually indicate conditional

statements required for description or simplification of the definition or law. For many students, particularly those who have some experience in mathematics or computer coding, conditional statements are quite familiar. The “IF” statement is well known in logical reasoning and the “IF.... THEN” statement appears in all geometry theorems. However, it seems that novice students are mostly unaware of the logical reasoning implied by the inclusion of conditional statements as they apply to physics, therefore the unthinking use of conditional statements contributes to student perceptions that physics concepts only have limited application in their daily life (Ferreira, 2014).

2.6.3 Simplifications

Because real world phenomena are influenced by multiple and complex variables which require advanced physics for prediction and mathematics for measurement of those phenomena, the knowledge to be taught is often manipulated for physics teaching by deliberately ignoring some disciplinary aspects. Real world phenomena are simplified by disregarding factors that are distracting (unwarranted) in terms of the underlying physics principles to be learned when introducing these principles to high school or undergraduate students (Champagne *et al.*, 1982; Duit *et al.*, 2014). However, the problem is that students have never been given any measures and ways of judging what to disregard and what not (Lubben, 2016). It should therefore not come as a surprise that simplifying the conditions of falling bodies to free fall with no resistance, for example, does not always simplify the problem (Gunstone, 1987). Student lack of awareness of the differences between everyday life and the simplified idealized science contexts used in physics results in failure to resolve discrepancies between experiential observations and idealized physics explanations (Gunstone & White, 1981; Ferreira & Lemmer, 2016). This failure leads to a belief that science applies only to special situations, thus hindering the development of student perception of physics as a coherent body of knowledge (Muis & Gierus, 2014; Von Aufschnaiter & Rogge, 2015). It would be helpful to their conceptual learning to make students aware of how to take the step from the real world into the theoretical world by abstracting those essential bits in the real world which are needed for theory making in the applicable context. Reconstructing certain aspects of everyday experiences under theoretical perspectives forms the basis of physics thinking (Duit *et al.*, 2014), therefore the inability to do this contributes to student difficulties in developing both an understanding of physics concepts and the ability to use that understanding to solve physics problems.

Simplifications and qualifying statements are justified, though, since they greatly simplify the mathematics involved in, for example, introductory mechanics problems by eliminating the variables associated with the effects of air resistance (Gunstone, 1987, Redish, 2014). For many students, however, this seemingly unjustified simplification calls into question the applicability of what they are taught. As a result, students doubt the integrity of physics as a coherent system of

concepts to accurately describe and predict real world phenomena (Sanborn, Mansinghka & Griffiths, 2013). An explanatory approach towards the use of conditional statements such as in the absence of air resistance in introductory mechanics likely clarifies and resolves the apparent discrepancy between the alternative conception of 'heavier objects fall faster', which students may experience every day, and the scientific Galilean's principle of free fall. Mathematically, ignoring the effect of air resistance is crucial, since it renders such problems tractable. However, this step is rarely, if ever, provided with any justification in school or undergraduate texts, leading students to believe that what they are taught does not apply to their everyday experience. Quite the complete opposite to 'justification of this simplification' often occurs in texts. In the case of objects in free fall, instead it is almost universally claimed (completely and totally and unequivocally incorrectly) that Galileo 'demonstrated' this unobservable generalisation (all objects have the same acceleration....) by dropping a pair of spheres from the top of the Leaning Tower of Pisa (and so making the separation of school physics from the real world even more extreme for many students) (see for example Gunstone, 2014:18). Taking the additional step of clarifying when it might be reasonable to ignore air resistance and when it might not, makes student reconciliation of their everyday experiences with the physics principle of free fall considerably more likely.

2.6.4 Multiple representations and their affordances

"A discipline is a way of knowing, and whatever is known is inseparable from its symbols (mostly words) in which the knowing is codified".

(Postman & Wiengartner, 1971:103)

The construction and use of representations are intrinsic parts of the discipline of physics and are consequently of critical importance in the learning and teaching of physics (Hestenes, 1987; Schwartz, Martin & Pfaffman, 2005; Zwickl, Hu, Finkelstein & Lewandowski, 2015). In the practice of science education, different representations of content matter are used in an effort to explain and encourage conceptual understanding of specific content. Each representation has a unique set of affordances, "the disciplinary knowledge that the physics representation has the possibility to provide" (Fredlund, C. Linder, Airey & A. Linder, 2014:9). A scientific representation involves a target system or phenomenon that is simplified to focus only on relevant features. It is described in terms of known scientific concepts and relations (principles) and represented with the aid of scientific diagrams, graphs, mathematical expressions, etc. (Zwickl *et al.*, 2015). Representations encode, describe, explain and predict key characteristics of real life events and processes using scientific representations.

Airey and Linder (2009) introduced the term ‘disciplinary-specific semiotic resources’ as a complementary depiction of representations. They differentiate between representations and semiotic resources in terms of the meaning that semiotic resources convey and how students construct that meaning. In addition to representations Airey and Linder (2009) also include tools and activities as concepts in disciplinary discourse. The term ‘disciplinary-specific semiotic resources’ encompasses the disciplinary way of knowing, the complex of representations, tools and activities of a discipline, which are made up of various “modes” in which discourse is conducted. Examples of modes are images, mathematics, apparatus, etc. In this thesis the term “representations” is intended to have the same meaning as the construct of “mode” used by Airey and Linder (2009).

Meaningful physics learning requires fluency in applying various modes of representations. Justification for the use of multiple representations is found in the dual-processing theory. According to the theory, the human brain has separate processing systems for verbal and visual input that can be used simultaneously. As a result, more can be learned from words and pictures than from words alone (Airey & Linder, 2009). As each representation has a unique set of affordances the use of multiple representations means the representations complement each other, and a carefully designed constellation of representations provides teachers with valuable instructional affordances (Fredlund *et al.*, 2014). Physics teachers therefore require knowledge of the affordance attributes of each possible representation of given material, as well as the contribution of each representation to the collective disciplinary affordance. Teachers should understand which representation/s to choose for a specific task, depending on the properties of the information to be presented, the material to be understood and the meaning-making potentials of the representations.

Using multiple representations for physics situations offers different affordances and may provide more opportunities to support learning (Wu & Puntambekar, 2012). Different representational systems for a certain physics event provide different levels of information, for example diagrams, in contrast with verbal representations. This allows students to visualize relationships between concepts and contribute towards deeper understanding of scientific phenomena (Treagust, Chittleborough & Mamiala, 2003; Wu & Puntambekar, 2012).

Motion diagrams are a standard form of pedagogical representation used in mechanics. In a motion diagram, which can have a physical manifestation via a ticker tape diagram, the object’s position throughout the motion is recorded at regular time intervals (with this being shown as sequential dots on a paper strip as if being created by a ticker timer). By comparing the distance between consecutive records (e.g. dots on ticker tape), the objects’ velocities and accelerations can be compared visually. In this present research, the concept of equal acceleration of two

moving objects was clarified by comparing their motion diagrams. The motion diagrams were intended to enhance student conceptual understanding by enabling a visualizing of the objects' motion and the linking of the motion and the different variables that applied to the motion diagram, for example, acceleration, velocity and displacement, to other representations of the same motion e.g. physics equations or graphs. This was also intended to enhance coherence of relationships between the different physics concepts. Examples of how multiple representations were used simultaneously are explained in Chapters 6 and 8 of the thesis.

2.6.5 Identifying student alternative conceptions

Various researchers argue that the main goal of an introductory mechanics course should be helping students to develop both a good understanding of physics concepts and the ability to use that understanding to solve physics problems (e.g. Duit *et al.*, 2014; Muis & Gierus, 2014; Von Aufschnaiter & Rogge, 2015). Studies on the influence of problem-context have evolved to allow teachers to evaluate student concept development and their level of conceptual understanding (Stewart *et al.*, 2007) via diagnostic tests such as concept inventories (refer to Section 2.3.3), for example the Force Concept Inventory (FCI) (Hestenes *et al.*, 1992). The value of the FCI as instrument for analysing student understanding of the concepts of force and motion has been established over many years (Treagust, 1995). The sets of multiple-choice answers for each item containing distractors that address specific alternative conceptions designed to discriminate between Newtonian and non-Newtonian responses. While the FCI concept test is designed to indicate how well the students understand concepts, it does not indicate how well students can apply the concepts in problem solving (Saul, 1998). This shortcoming can be overcome by adapting applicable items in standardized tests and converting them into 'isomorphic questions' (Ferreira & Lemmer, 2016), a term used with the same meaning as the term 'Elby pairs'.

Elby pairs are paired questions consisting of one question which most students are likely to answer correctly and another question in which students will likely fall back on their naïve knowledge while applying the same concept (Hammer & Elby, 2003; Redish, 2006; Dreyfuss, Gupta & Redish, 2015). By comparing the way in which students apply the same concept in different situations, inconsistencies in their reasoning are revealed. The concept of Elby pairs corresponds with the proposal by Minstrell (1982) to contrast alternative conceptions with physics concepts, and thereby reveal the existence and nature of student alternative conceptions and the reasoning behind naïve (experiential) knowledge (Minstrell, 1982; Muis & Gierus, 2014). The acquired knowledge that objects in free fall have equal acceleration is easily applied in questions for which the context is similar to that in which the knowledge was learned (see Section 2.3.3). Once the context changes, however, the lack of conceptual understanding of the concept of free fall and its implications is revealed. The paper "Alternative conceptions: Turning adversity into

advantage” (Ferreira, Lemmer, and Gunstone, 2015) included in Chapter 4, Section 4.6, describes how generally used questions can be implemented to identify student alternative conceptions by changing the direction, plane or variable in which such a question is posed.

2.6.6 Content knowledge: Free falling bodies

Some of the literature in this as well as the following section is included in Ferreira, Seyffert *et al.*, (2017); this paper is included in Chapter 8 of this thesis.

The alternative conceptions relating to gravity and the Galilean principle of free fall are of particular interest in this research. One of the most reported alternative conceptions in introductory mechanics is that ‘heavier objects fall faster’, which conflicts with the Galilean principle of free fall. It is clearly observed that, if they fall far enough, heavier objects do indeed fall faster. Hence one of the complications here is that for many students their observed experience counters the physics assertion of equal times of fall for objects (i.e. equal accelerations) in a uniform gravitational field. This Galilean principle of free fall, when presented without qualification or explanation of the conditional statements that are usually included, hinders students in their attempts to solve problems where a physics conception of free fall is crucial because it contrasts with their daily experience. Examples used to introduce and assess the concept of free fall typically describe the motion of two objects (usually equally sized balls with different masses) being dropped simultaneously from the same height (see for example Item 1 of the FCI, Hestenes *et al.*, 1992). If a student who believes that heavier objects fall faster is asked to predict which ball will hit the ground first in such an example, ignoring air resistance, they generally answer that the heavier of the two balls will hit the ground first. The rather complex issue of occurrences of conflict between actual observations of falling bodies and the Galilean simplification of equal accelerations under a uniform gravitational field are considered in detail in Chapter 8.

There are some critical issues that pose difficulties in conducting experiments to demonstrate the effect of air resistance. For example, as de Obaldia *et al.*, (2016) pointed out human reaction times are relatively longer than the times falling objects take to reach the ground. This makes it difficult to determine the velocity of falling objects. Also, the qualification of equal sizes for two balls typically described in examples to explain the equal acceleration, is rarely emphasized, and students consequently do not consider it to have an influence on the motion. The size of the balls, specifically the cross-sectional area A_c of each, plays an equally important role in the determination of the motion. However, discussions regarding its impact are generally limited to specific and rather obvious examples such as a parachutist experiencing a substantial increase in drag (air resistance) when the parachute is opened. Such examples are usually intended to

illustrate the concept of terminal speed, and neglect to point out that both mass and cross-sectional area are important when considering the magnitude of the experienced force due to air resistance. For example, in comparing the motion of a leaf and a nut falling from the same tree and the nut landing first, the difference in motion is more often explained in terms of the bigger mass of the nut than in terms of the bigger cross-sectional area of the leaf. Having little or no knowledge of air resistance, students do not realize that a heavier object is relatively less restricted by air resistance while a bigger object is more restricted by air resistance, and that the real falling rate (along with the air resistance coefficient) is determined by a combination of both A_c and mass, and factors such as the shape of the object. As a consequence, students tend to focus only on the influence mass has on the motion, concluding that heavier objects fall faster.

There has been a number of previous explorations within the context of physics education of the effect of air resistance on falling bodies. Grant (1990) investigated the effect air resistance has on a variety of school sports involving projectile motion. Kincanon (1990) used available data on skydiving and compared it with theoretical predictions in an example for teaching about resistive forces. Agrawal (2000) investigated the relation between a skydiver's mass and terminal velocity in the horizontal spread eagle position. Theilmann and Apolin (2013) and Greening (2013) both investigated supersonic free fall, specifically discussing the record-breaking jump of Felix Baumgartner (an Austrian skydiver, daredevil and BASE jumper) also known as the Red Bull Stratos space diving project. Both of these latter papers focused on the relationship between air density, air resistance, and the resultant effect on terminal velocity, but Theilmann and Apolin (2013) also modelled the free fall itself. The results reported by Kincanon (1990) and by Agrawal (2000) are of particular interest for my research. The relationship between air resistance and the surface area of the falling object (Agrawal, 2000) and the comparison of real data and theoretical predictions (Kincanon, 1990) resonate with what I have done. However, I have used the relationships in a slightly amended way. As detailed in Chapter 8, I compared the effect of air resistance on objects with different mass and sizes in an attempt to predict when it would be reasonable to ignore the effect of air resistance, i.e. when can a falling object's motion be regarded as being equal to free fall, even in the presence of air resistance.

2.7 Conclusion

From the body of literature, I have justified the importance of the concept of acceleration for this study. The literature shows that the relationship between force and motion not only applies to mechanics but lays the foundation on which all physics is built. In terms of the force to mass ratio, acceleration links the dynamics of forces as the cause of changes in motion with kinematics in terms of the extent of, and the consequences of, those changes. These consequences include, but are not restricted to, the displacement-velocity-time relationship with acceleration.

In the next chapter the research design and methodology for this study is presented, followed by the data chapters.

CHAPTER 3: RESEARCH DESIGN

3.1 Introduction

The methodology and research design with which this research study was approached was a consequence of the fundamental research question posed in Chapter 1: What circumstances will foster better understanding of concepts such as acceleration and its conceptual relationships, in the topic of motion in free fall? In this study the specific focus is on linear motion under gravity and the poorly understood net force-mass-acceleration relationship. The more detailed research questions that guided each of the five successive iterations of the investigations are found at the beginning of each of the sub-sections of Section 3.5 that contain brief and individual descriptions of these successive iterations.

In Chapter 2 central issues in the domain of teaching and learning introductory mechanics were discussed, as were the specific ideas on which this research is focussed. In this chapter I argue that the conception of Design-Based Research (DBR) as used in this thesis is a logical consequence of the fundamental research question.

I begin by briefly considering some implications of the core issue (the ‘conceptual framework’) underpinning my research motivations. This is followed by a more detailed discussion of the rationale for choosing the DBR methodology and an overview of the methodology. DBR is specifically presented here as a research methodology with clear goals of linking research and practice so as to enhance the understanding of conceptual relationships associated with motion under gravity.

After these discussions of overarching methodology issues of sampling, descriptions of the data collection methods, the analysis relevant to the quality (reliability and validity) of the research instruments, the data obtained and the interpretation of the data are considered. The results of the different iterations, central to the nature of DBR, are very briefly described so that the nature of each consequent iteration can be justified. What I present in this chapter is a “discussion of the study’s design or the argument for the logical steps which were taken to link the research questions and issues to data collection, analysis and interpretation in a coherent way” (Hartley, 2004:326).

3.2 Conceptual framework

The paradigm in which research is undertaken provides the theoretical, methodological and instrumental foundations for the study, that is, the concepts, assumptions, expectations, beliefs and theories that support and inform the thesis work. The philosophical stance taken in this study

is that the research process used is a logical consequence of the research questions. i.e. the study adopts a question-driven approach (Robertson, Scherr & McKagan, 2013). The question-driven approach and methodology also impacted on the instruments developed/chosen to execute the research.

The nature of the research required an approach chosen on the basis of its functionality. To answer the research questions and to find possible solutions for the issues I wanted to address, it was not practical to commit to only one research approach. A pragmatic paradigm for a study allows a researcher to blend methods when a single research theme instigates multiple research questions, each of which calls for a unique methodology. It allows freedom to commit to qualitative and quantitative methods, and to choose procedures and techniques that are best suited for the purpose and needs of the research (Alghamdi & Li, 2013; Creswell, 2007). Adopting a pragmatic research paradigm enabled the use of a series of methods to look at the “what and how” of different approaches based on the intended consequences thereof (Alghamdi & Li, 2013; Barab & Squire, 2004). The freedom of choice in the methods, procedure and the techniques of research that best fitted the needs and purposes of the present study (Alghamdi & Li, 2013) eventually lead me to DBR.

3.2.1 Justification for the choice of DBR

In the early 1990s researchers began calling for integration of both fundamental and applied research to improve teaching, learning, and instructional resources (McKenney, 2016) as traditional research approaches to that time were unsuccessful in providing guidelines useful for design and development problems in education (Van den Akker, 1999). With this in mind and in the process of choosing a suitable approach for the present study, two other research approaches were considered and discarded.

The first of these approaches, namely an experimental study, was considered only briefly. The extensive previous research trying to understand how to foster conceptual change and the nature of my fundamental research question made it clear that a purely experimental study would have very little prospects of advancing our understanding. While many experimental studies point out various difficulties and deficiencies, most are ‘one shot’ treatments, like direct refutation of an alternative conception for example. It is widely shown by more than 35 years of research, particularly but not only in mechanics, that these kind of single treatment studies have had extremely limited success in fostering conceptual change. There is an extensive body of literature that reports on the failure of experimental studies to produce the desired conceptual change - for extensive references see the bibliography by Duit (2009) and more recent reviews of research, for example by Von Aufschnaiter and Rogge (2015). (Note that although Duit has not updated his

bibliography since the last edition in 2009, it remains today an invaluable and unique resource for research on alternative conceptions and conceptual change as it contains literally thousands of research papers, all categorized by science content considered and other variables.) It is also clear that an experimental design would have been inappropriate for my research as I concluded from extensive considerations of past research that I needed to look at a much finer level of detail, a much finer grain, than many previous investigations of conceptual change. Further, this much finer level of detail was needed for both the physics *per se* and the learning of that physics. A research approach that allow for cycles of investigation to be repeated was clearly of relevance to this issue of fine grain.

A second possible approach that was considered, and that would allow for repetitive cycles of investigation over a period of time, is action research. The purpose of action research is to develop a solution to a practical problem which is consistent with research that aims to bridge a gap between the theoretical and the practical aspects of research (Alghamdi & Li, 2013). However, a central practical matter in the various forms of study that tend to be grouped under the label of action research were not available to me: circumstances meant I could not be the usual teacher of the students who participated in the study (I did not have ongoing classes with whom I could conduct long term studies), and as the classes that could be used were not my normal classes I could not involve them over a lengthy period of time. Therefore, action research was not an option for me to use.

A methodological approach that has not often been attempted in conceptual change research, an approach where a single research theme instigates multiple secondary research questions, is to consider one or two issues at a time and investigate what the consequence of responding to each issue is. As DBR allows flexible design revision considering multiple dependent variables (Barab & Squire, 2004) that was the approach most suited for this study. One of the characteristics of DBR is iterative cycles of change, cycling back through issues with successive shifts and changes, an advantage that action research does not allow (unless one waits for the following year to implement the revised investigation at the same relevant time in a curriculum). The argument for the choice of DBR is that it was a logical consequence of the research questions because, fundamentally, from the whole set of different approaches to research design, no other approach was as suited to the fundamental research question and what was already known about this, or as practical for me to use.

3.2.2 DBR as methodology

DBR is one of a genre of approaches that connects basic and applied educational research. Although DBR uses existing research methods, often mixing qualitative and quantitative methods,

and follows well-known norms for sampling, data collection and analysis, its goals and aims and approaches set it apart from other categories of research. In DBR the goals of basic and applied research are blended to derive new knowledge by designing and implementing solutions to problems in educational practices (Barab & Squire, 2004; McKenney, 2016). Figure 3.1 below is a diagrammatic representation of the DBR process.

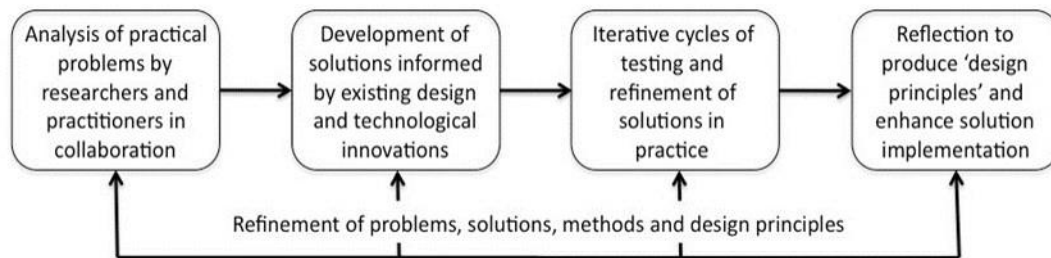


Figure 3-1: Diagrammatic representation of the DBR process

(attributed to D. T. Jones sourced from Flickr and reproduced under a Creative Commons License)

Among its other defining characteristics, the iterative nature of cycles of design and evaluation of solutions to practical problems is one of the most significant characteristics of DBR. Wang and Hannafin's (2005:6) description of DBR as "a systematic but flexible methodology aimed to improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real world settings, and leading to contextually-sensitive design principles and theories" captures the essence of DBR (see also Alghamdi & Li 2013; McKenney & Reeves, 2013; Psillos, 2015). Fundamentally, this is how I have used DBR (with three core differences noted in Table 3-1 below) in my research. In section 3.2.4 I show how my study aligns with the characteristics of DBR as well as how it differed from Wang and Hannafin's (2005) description in terms of the collaboration between practitioners and theory development.

The phrases "iterative analysis, development, and implementation" used by Wang and Hannafin (2005:6) represent the ways in which the relevant aspects are recycled in this research. Other writers have perspectives that are broadly similar and which are helpful to conceptualize this methodology and its merits. Although the details of how each perspective pictures DBR may vary, all agree that DBR consists of a number of iterative cycles (see Figure 3-1) (Alghamdi & Li, 2013; McKenney & Reeves, 2013; Plomp, 2010; Psillos, 2015; Van den Akker, 1999; Wang & Hannafin, 2005).

Some researchers use the term "phase" to refer to these cycles, a few use "phase" to refer to components within a cycle. In order to avoid any such confusion, from this point in the thesis I

use the term “iterations” to refer to the iterative cycles, “parts” to refer to components of an iteration, and “sub-part” to refer to any further division of a “part”. Where components of a part consisted of or included an experiment I refer to such “sub-part” as an “activity”.

In summary, the central features of DBR are that it is iterative; interventionist; takes place in naturalistic contexts; and is concerned with impact on practice (Barab & Squire, 2004:2-3). DBR thus generates products that are useful in both improving educational practices and generating accompanying scientific insights into how these products can be used in education (Van den Akker, Gravemeijer, McKenney & Nieveen, 2006).

3.2.3 What knowledge does DBR offer: The merit of the design

Design-based research (DBR) as used in a wide range of educational contexts evolved as a practical research methodology that could close the gap between research and practice in formal education (Anderson & Shattuck, 2004). The specific processes adopted in DBR by various researchers are more diverse than some descriptions of DBR models give it to be (e.g. Visscher-Voerman & Gustafson, 2004). Many authors over the years have produced different descriptions of possible detail of a DBR approach (e.g. Anderson & Shattuck, 2012; Barab & Squire, 2004; 2004; McKenney & Reeves, 2013). Opinions differ on various elements of the practice of DBR, for example and most obviously, on the role of theory. Plomp (2010:11) refers to the “twofold purpose” of DBR which he describes as “to develop research-based solutions to complex problems in educational practice OR to develop or validate theories about learning processes, learning environments and the like” (emphasis added). According to McKenney and Reeves (2013:98) “ONE of the main goals of DBR is to generate theoretical understanding that can be of value to others” (emphasis added). Literature on how design practice actually takes place indicates that while some design solutions are informed by research investigations and theory, other design solutions were developed “through engineering of locally functional solutions” and “applied to the problem without waiting to develop a deep theoretical understanding” (Joseph, 2004:235, 238).

Plomp (2010:16) distinguishes between two kinds of design studies namely, developmental studies and validation studies. Nieveen, McKenney and Van den Akker (2006) make the same distinction as they perceive development of design principles as part of developmental studies, they do not attach design principles to validation studies. The main difference between these two (development and validation) is the purpose of the researcher (i.e. of the study). Developmental studies seek to “develop research-based solutions for complex problems in educational practice” while the purpose of validation studies is the development or validation of a theory (Nieveen *et al.*, 2006:152). The central point here is not that one opinion is better than another but that there

is a range of opinions regarding the complexities and nature and use of DBR, as is also true for researchers working in a range of other complex methodologies (e.g. self-study of teaching) and with a wide range of complex constructs (e.g. 'pedagogical content knowledge' or 'scientific literacy').

The fundamentals of DBR are not necessarily embedded in developing or validating theory but always have a central focus on problems embedded in and derived from educational practice. The commonalities that the many different detailed descriptions of DBR share are the characteristics of a quality DBR study (Anderson & Shattuck, 2004; Joseph, 2004; Wang & Hannafin, 2005; Van den Akker *et al.*, 2006; Plomp, 2010). For educational research these characteristics, as described by the authors just cited, are that DBR begins with a clearly demonstrated problem being situated in educational practice involving something that is significant for that practice, for example, the learning of fundamental concept[s] in mechanics. Researchers then seek to design and test interventions to address the problem using mixed methods, implementing multiple iterations for which each successive iteration is informed by the results of the previous iteration. The process usually involves a collaborative partnership between researchers and practitioners due to their respective fields of expertise, however, there are instances where the researcher can also be responsible for design and practice because the researcher also has clear practitioner experience (Joseph, 2004). Because of the use of multiple iterations, with the results of each revised approach evaluated, the DBR methodology maximises the chances of moving towards a better approach for solving the problem. Whether or not this process begins with generation of theory is a function of the nature of the motivating educational problem, what is known about the origins of the problem, and what has previously been attempted by way of seeking to resolve the problem.

There is considerable support in the literature for DBR and its value as a method (Anderson & Shattuck, 2012; McKenney & Reeves, 2012; McKenney & Reeves, 2013; The Design Based Research Collective, 2003). As such, DBR's contribution to the body of knowledge in the field is strongly advocated by a range of authors as a mode of educational research that can provide information about the *more effective ways* of achieving stated learning goals. Van den Akker *et al.* (2006:5) use the term "utility oriented" for the iteration in which "the merit of a design is measured in part by its practicality for users in real contexts", i.e. it has value beyond the researcher. Plomp's (2010:19) third iteration of DBR is named the 'assessment' iteration which includes some form of summative evaluation to i) determine whether the intervention met the expected outcomes and ii) inform improvement of the intervention to achieve the stated learning goals. In a real world setting DBR has developed as a reaction to the failure of traditional research methodologies to "link theory and practice within educational research, and as a means of

generating useful knowledge to guide educational practice” (Alghamdi & Li, 2013:3). A major aspect of DBR is the usable knowledge: its results contribute to the body of knowledge in the field to “effectively bridge the chasm between research and practice in formal education” (Anderson & Shattuck, 2012:16), a position that is supported by Barab and Squire (2004:8) who refer to the knowledge gained from DBR as the “usefulness or consequentiality of the work”.

The practicality of the design of this present study was supported in a number of different ways. For example, the practical significance of a specifically designed teaching sequence, that included a tutorial on a conceptual approach to acceleration and proportional reasoning focussed on enhancing student understanding, is supported by inferential statistical analyses of the data obtained during the sequence, and a set of graphs was developed to simplify explaining the effect of air resistance.

In summary, DBR as a research approach is well suited for this study to seek and provide responses to the fundamental research question of how circumstances can be created for better understanding of the specific ideas or concepts that are known to be not clearly understood.

3.2.4 How DBR is used in this study

Although Van den Akker *et al.* (2006:5) use terms that differ from those used by Plomp (2010) and Wang and Hannafin (2005) to describe some of the issues that characterize DBR there are broad similarities between these three descriptions. In Table 3-1 below I use five categories proposed by Wang and Hannafin (2005) to describe DBR, in conjunction with relevant descriptions of DBR by Van den Akker *et al.* (2006:5) and Plomp (2010), as a frame to describe the principles of DBR and my practical implementation of it. There are three core differences from the description of Wang and Hannafin (2005) in the way I have used DBR in my research, the first one relating to theory development (see row 2b of Table 3-1) and two differences involving issues of collaboration between practitioners (see row 4, Table 3-1).

Table 3-1: Characteristics of DBR and how it is used in the study

Category/feature of DBR	How it was used in this study
1. DBR is pragmatic; its goals are solving current real world problems This feature of DBR is described by Van den Akker <i>et al.</i> (2006) as in response to a problematic situation or need, by Plomp (2010) as informed by research prior to the study.	My study was initiated by prior research that indicated that the persistence of alternative conceptions of motion under gravity was a continuous factor in inhibiting student conceptual understanding of the concept of acceleration. My goal was to develop and refine an approach that could

Category/feature of DBR	How it was used in this study
	eventually lead to improvement of educational practice, specifically the teaching and learning of acceleration.
2a. The DBR is grounded in the real world context with the complexities, dynamics and limitations of authentic practice. The “interventionist” iteration (Van den Akker et al., 2006) aims at designing interventions in a real world setting; this concurs with “improve educational practices through design, development” (Wang & Hannafin, 2005).	My successive interventions - a teaching sequence, a teaching experiment and a further teaching sequence which included a tutorial - were done in the “messiness of real world practice” with post-school students in normal class situations (refer to section 3.3)
2b. The DBR is grounded in theory Van den Akker et al. (2006) term this iteration “Theory orientated”, the systematic evaluation of the intervention contributes to theory building, while according to Wang and Hannafin (2005) DBR leads to design principles and theories.	This is the first core difference in my usage of DBR; because the central problem for which I was using DBR is one which involved both analysis of very specific aspects of physics per se and development of alternative approaches to enhance understanding of these specific concepts. While these approaches were certainly embedded in existing theories (see Section 3.2.4) any theory development was a secondary issue for the study.
3. DBR is interactive, iterative and flexible Van den Akker et al. (2006) use the term “iterative phase” (referring to an iteration) which relates to Plomp’s (2010) “prototyping” iteration, and the characterisation of Wang and Hannafin (2005) of DBR as interventions to be continuously developed and refined through an iterative design process from analysis to design to evaluation and redesign	Each iteration in this research study was informed by the evaluation, analysis and revision of the preceding iterations, as needed. The similarity in the iterations is that each of the iterations in this study included the clarification of conditional statements which were shown to (or inferred to) contribute to student alternative conceptions. The content of subsequent iterations differed in accordance to some aspect that emerged from the previous iteration, for example, the mathematical approach to acceleration was not repeated in successive iterations. A brief description of each iteration of the DBR is given in Section 3.5 of this chapter.
4. DBR requires interactive collaboration among researchers and practitioners. Van den Akker et al. (2006) describe this feature as active participation of practitioners in the various stages and activities of the research. Wang and Hannafin (2005) describe DBR as being based on collaboration involving both researchers and teachers.	Two of the core differences in the way I used DBR in my study are with regard to the involvement of practitioners. Firstly, because this is a thesis study the collaboration among researchers was much more collaboration with my supervisors, although I also had intermittent discussions with science education researchers from two other universities at different times. Secondly, although the samples used for some iterations involved student teachers or practising teachers in professional

Category/feature of DBR	How it was used in this study
	development programs, these were not collaborating practitioners in DBR terms, but physics learners (that is, these groups did not already possess understanding of the physics concepts and relationships involved – refer to section 3.3).
5. The DBR is evaluated and its merit is measured by its usefulness in practice: This is termed the “Process oriented” iteration by Van den Akker et al. (2006). Van den Akker et al. (2006) use the term “Utility oriented” to indicate DBR’s practicality; the definition of Wang and Hannafin (2005) contains the phrase “improve educational practices through implementation”; It is consistent with the processes of analysis, design, development which serves to confirm and enhance the “credibility” of findings described by Wang and Hannafin (2005:8) and with Plomp’s (2010) “Assessment” iteration “where evaluation is done to decide whether the solution or intervention meets the pre-determined specifications.”	In each one of the experimental iterations data were collected and analysed. The extent to which the iteration met the expected outcomes was evaluated either by qualitative content analysis or quantitative inferential statistical analysis. This DBR feature agrees with the qualitative results collected in two of the iterations of this study aimed at understanding student perceptions and experiences of the alternative approach on acceleration. The results of the analysis informed the subsequent iteration. The merit of DBR and the practicality for my study in particular is discussed in more detail in the previous section - Section 3.2.3.

3.2.5 Validity of DBR

The acceptance of DBR as a valid approach to research has already been established (Barab & Squire, 2004; McKenney & Reeves, 2012; McKenney & Reeves, 2013; McKenney 2016). The most significant form of validity to consider, particularly because it is a logical consequence of DBR, is a form of validity which is rarely mentioned but critical if one is really concerned with real teaching in real classrooms – ecological validity. To explain how ecological validity relates to my study I draw on the initially accepted description of the construct, that ecological validity refers to the extent to which the findings of a research study are able to be generalized to real-life settings (Bronfenbrenner, 1977), and the altered description posed by Bronfenbrenner (1977:516) that “Ecological validity refers to the extent to which the environment experienced by the subjects in a scientific investigation has the properties it is supposed or assumed to have by the investigator”. Barab and Squire (2004:3) argue that it is the focus of DBR on understanding the “messiness of real world practice, with context being a core part of the story” that sets it apart from traditional research methods.

McKenney (2016:155) argues that cognitive scientists have been especially concerned with finding ways to derive empirical insights that are ecologically valid. As this present study is about research focussed on improving particular real learning and teaching issues of importance, and the argument being presented at this point is about why it is appropriate to use DBR, then it is 'ecological validity' that is most important to consider with respect to the validity of the research: that is, validity in terms of how well the study does embrace the real world of well-known classroom learning problems, and how well it uses real world learners who know they actually need to learn the content. As all DBR has broadly consistent concerns of real problems of teaching and learning and finding ways to reduce these problems, it was logical to embed this research in contexts that represent the reality and normality of teaching this content, i.e. real classrooms with intact classes learning content that was known to be part of their real curriculum.

3.3 Sampling

One of the complexities in undertaking DBR is that there are major and complex problems in attempts to use the same sample for successive iterations. Because each iteration has caused some learning in the group with whom that iteration was conducted, then using the same group for iteration 2, and/or 3 means the 'starting point' of the group is now not typical of learners; so one no longer has a 'fair test' for iteration 2 or 3. The central issue with the group of participants in each of the iterations in this study is that all groups were constant in that these were learners who had good reason to try and come to understand the fundamental ideas of classical mechanics. The participants were all learners of physics and they were all samples of convenience. The details of the number of participants and the rationale for each particular sample with each iteration, are given in the methodology section of the relevant chapter on that iteration.

All of the samples used in this research are post-high school students of physics. The samples in the different iterations of the research are in some detail different, but all have a most significant common feature: they are all committed to try to *understand* the concepts addressed in the iterations. They were either undergraduate first-year physics students, or in-service physics teachers in a professional developmental program, or third-year Physical Sciences pre-service student teachers. The samples used in each of the iterations are a consequence of the education system in which I am working. In South Africa it makes sense to look at the students who are studying physics post-high school as the levels of physics one might expect to be reached in school are significantly lower than, for example, A-level physics in the United Kingdom.

A central issue in research in science *per se* is to minimize variables that impact on the research that is being done, even in DBR conducted in "the messiness of real world practice" (Barab &

Squire, 2004:4). One way to argue the appropriateness of the set of post-high school samples that I used is that I am looking in an environment where, if there is any progress to be made, this is more likely to be found. To describe this reduction of variables I use a term suggested by Gunstone (2017) - one is seeking to “minimize the noise” in the research context. To prevent the misconception that reducing noise implies an artificial laboratory-like research environment, I explain the reduction of noise and the linkage with science and ideal conditions as a parallel with the approaches of science. The scientific approach since the Enlightenment has often sought to understand phenomena in ideal circumstances by controlling as many variables as possible, and then subsequently to explore the extent to which the explanation holds up when all of these variables come flooding back in. For example, Boyle’s law in its precise mathematical form is applicable only when there are just two variables (pressure and volume of a gas) in a laboratory situation. When applied to car tyres it is a good estimation but it is no longer precisely true, particularly when the car has been driven some distance and temperature of the gas has increased.

Using a set of post-high school samples meant that I could ‘reduce the noise’ (diminish the significance of additional variables) that would have come with high school physics students who would necessarily have achieved lower levels of physics knowledge and understanding, and very likely have been less motivated to work to understand and more motivated by the nature of examinations. Once an understanding of phenomena or relationships is established in ‘low noise’ settings such as those used in the present research, then one can later look at the understandings or otherwise that can be fostered in more normal conditions, to see if these understandings are robust enough to be helpful in conditions of normal noise. It is a separate and later issue to see if the results of this study will have value in high school physics (Physical Sciences in the FET band, grades 10 to 12, in South Africa).

3.4 Design principles inferred from the literature

The consensus across a wide range of literature about DBR is that the most significant outcome of a DBR study is to attempt and bridge theoretical research and educational practice (Alghamdi & Li, 2013; Anderson & Shattuck, 2004; McKenney & Reeves, 2013; The DBR Collective, 2003). Specific principles which are implicit in designing the intervention to address the problem can usefully be expressed as a pair of rhetorical questions: What does the intervention[s] tell us that might be useful for other contexts/problems beyond the specific content of the DBR research? How does the intervention[s] result in a better understanding of the important and practically embedded problem which was the reason for undertaking a DBR study in the first place? These principles that flow from the literature study are made explicit and elaborated on in the following section.

The literature has lead me to infer two groups of design principles. One is a set of principles that have applied to all iterations in this DBR and will be laid out first. The second is a set of specific emphases of parts of the first set that guided each of the iterations. I conclude with a specific principle unique to the last iteration.

3.4.1 Design principles underpinning conceptual change

- **Design principle 1:** Adhere to the constructivist approach: Determine what student current conceptions and knowledge are and build on those.
- **Design principle 2:** Consider the links between the real and the physics worlds.

Especially the need for and consequences of conditional statements that attempt to simplify the physics that applies to the real world.

- **Design principle 3:** Identify core concepts in the content material that need to be enhanced.
- **Design principle 4:** Establish conceptual coherence in students' physics knowledge.

Two forms of coherence that are needed for “conceptual coherence in physics” are coherence across representations used in physics and coherence across the concepts of physics.

3.4.2 Principles that were emphasized in the different iterations

Iteration 1: Design principle 1 was emphasized to determine the extent of student alternative conceptions regarding free fall and the influence of air resistance.

Iteration 2: Design principle 2 was emphasized in terms of the links between the real world and the physics world in considering the conditional statements of “in the absence of air resistance and friction”. The core concepts that were emphasized in accordance to design principle 3 were net force and acceleration. In accordance with design principle 4 specific representations to i) enhance understanding of gravity as the net force for free falling objects and ii) introduce qualitative reasoning to advance conceptual coherence were implemented.

Iteration 3: The emphasis of design principle 3 here was on acceleration as the net force to mass ratio. To enhance conceptual coherence, design principle 4, a conceptual qualitative approach to acceleration as the net force to mass ratio was introduced.

Iteration 4: The addition to this iteration was in terms of design principle 4: Using equations as reasoning tools. The qualitative conceptual approach to acceleration as the net fore to mass ratio was linked to representations that supported visualisation of the net force, e.g. force diagrams

and motion diagrams. Using the affordances of the representations mentioned above, an introduction of the qualitative use of equations as reasoning tools followed.

Iteration 5: The very specific unique combination of principles 2 and 4 for this iteration was to create a clear, accurate and detailed mode of visually representing the motion of a range of objects in free fall that represents both “reality” and “ignore air resistance” situations.

3.5 Descriptions of the progression of this DBR

Full details of the different iterations undertaken in this research are given in context with the resulting data in the relevant chapters (Chapters 4 to 7). What follows here is a brief description of each iteration to show how the research unfolded as each subsequent step emerged as a logical consequence of the previous step. The first two iterations of the research were conducted with small groups of students, and the third iteration that resulted from the preceding two was conducted with an introductory physics class of almost 300 students. This is consistent with the characteristic of DBR of empirical investigations being conducted in real learning settings (McKenney & Reeves, 2012).

3.5.1 Research prior to this study

Research for my Master’s degree identified student problems, due to the persistence of alternative conceptions, with the application of kinematic relationships in contexts where the direction and/or plane of motion, and/or the physics variable to be solved in a given problem differed from the familiar vertical downward motion and from where the time of falling objects had to be compared. A report of the study has been published in the proceedings of the 2015 conference of the European Science Education Research Association (ESERA) (Ferreira and Lemmer, 2016) and is included in Appendix A. Concerns about particular issues that emerged from the Master’s research (Ferreira, 2014), for example demonstrable learning problems with conditional relationships, qualitative use of formulae, force-mass-acceleration relationships, were the driving force behind the conduct of grounding this research, the next logical step.

3.5.2 Iterations to implement possible solutions

The first iteration of the study is described in detail in Chapter 4, the second iteration in Chapter 5, the third in Chapter 6 and the fourth in Chapter 7. In Chapter 8 a final iteration is described. The detailed research questions presented in the descriptions of the different iterations in the relevant sections below are useful to summarize the core purposes/focus of what I did in each of the iterations. A diagrammatic summary of the iterations of the study is presented in Figure 3-2.

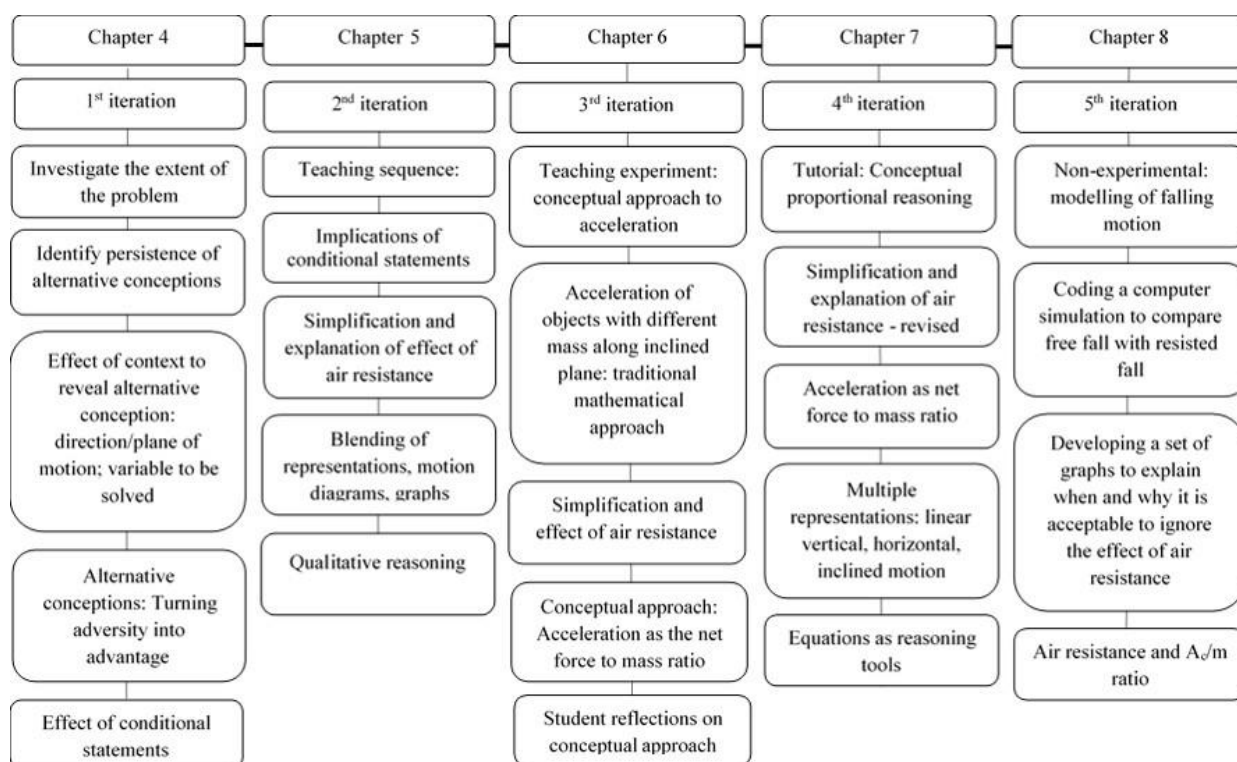


Figure 3-2: Summary of the iterations of the DBR

3.5.2.1 First iteration: Exploring the extent of student alternative conceptions regarding free fall and the influence of air resistance

The research questions for this thesis emerged from my Master's study of students solving kinematics problems in various contexts (Ferreira, 2014). I purposefully undertook the first iteration of the research as an analysis and determination of the extent of the problem identified in research prior to the study, namely, the difficulties that inclusion of the conditional statement of ignoring the effect of air resistance and friction caused in student understanding of simplification of real world situations, and the coherence of physics concepts. The detailed research question for this first iteration was: To what extent does changing the physics context of questions on linear motion under influence of gravity only influence student responses to paired comparable questions? Inferential statistics were used to analyse the data and the McNemar effect size was calculated to indicate the practical significance of the trends that were identified. The results of the first iteration are presented in Chapter 4. The execution and the results of the quasi-longitudinal research which pertains the first iteration is described in Ferreira, Lemmer *et al.* (2017), included in Chapter 4, Section 4.6. The results obtained in this first iteration and the widespread and robust and consistent impact of alternative conceptions on student learning drove me to look at ways to explain and clarify the use of conditional statements in the usual presentation of physics concepts and relationships. It seems clear that while inclusion of conditional statements does indeed simplify the *teaching* of physics, the simplification that is

intended with these conditional statements actually contributes to student difficulties in developing conceptual understanding of the core concepts of net force and acceleration.

3.5.2.2 Second iteration – enhancing conceptual coherence

My focus in the second iteration was, with an overall focus on motion of bodies in free fall, to consider to what extent does a) explanation of conditional statements and b) the use of multiple representations of motion in different contexts contribute to student understanding of i) the concept of net force and the acceleration associated with net force, and ii) the conceptual relationships between the physics variable for motion under gravity? As a result of the data concerning student problems with application of the kinematic relationships obtained during the investigation that grounded the research, I decided to address the very common and most persistent alternative conception that “heavier objects fall faster” by clarifying the conditional statement of “in the absence of air resistance”. To consider the effect of clarifying the conditional statement on student conceptual understanding of the kinematic relationships of falling objects in terms of the net force to mass ratio, I implemented in iteration 2 a teaching sequence which included combining affordances of various representations (blending of multiple representations) and introducing qualitative reasoning by using equations as reasoning tools.

The results of the second iteration indicated that explaining the use of conditional statements through multiple representations and considering equations as reasoning tools had a positive effect on student understanding of the concept of net force as applied to free fall. In addition, linking of the affordances of various representations, in particular the affordances of motion diagrams to those of graphs and of equations, not only appeared to enhance conceptual coherence of multiple representations but also served to assist student qualitative reasoning about the relationships embedded in kinematics equations. Subsequent iterations included different repetitions of relevant parts of the teaching sequence from the second iteration.

3.5.2.3 Third iteration – a conceptual approach to teaching acceleration

I describe the third iteration as a ‘teaching experiment’ because it contained a practical experimental component, and to distinguish it from the other iterations which did not. The more detailed research question guiding this iteration was: what is the effect of a conceptual teaching approach to acceleration as the net force to mass ratio on student understanding of i) the concept of acceleration and ii) the qualitative use of proportional relationships in terms of Newton’s second law? Informed by results of the second iteration and the data about student learning in terms of the clarification of conditional statements and the effect of air resistance on falling objects, I decided to implement a teaching experiment based on conditional statements about the effect of

air resistance and a conceptual approach to acceleration as the net force to mass ratio. This next step required designing a teaching experiment on acceleration that contained both the traditional mathematical approach to acceleration (acceleration as the time dependent change in velocity) and a conceptual approach to acceleration as the net force to mass ratio. The qualitative results from the students' reflections on the approach to teaching acceleration as a conceptual proportionality indicated that the improvement in student conceptual understanding of acceleration was promising. However, the results also suggested that more work was required to help students relate different physics quantities through qualitative and/or proportional reasoning.

3.5.2.4 Fourth iteration – introducing equations as reasoning tools

The more detailed research question for this iteration emerged from the results of the previous two iterations: How will an approach consisting of i) an alternative representation of acceleration as the net force to mass ratio, ii) blending of representations, and iii) introducing equations as qualitative reasoning tools in comparative proportional reasoning (from here on referred to as qualitative reasoning) influence students' conceptual understanding of i) the concept of acceleration and ii) the conceptual relationships involving acceleration? Based on the data about the positive effect of the alternative approach to acceleration as the force to mass ratio in the second iteration, I designed a teaching sequence which was a combination of the previous two iterations, and to explore to what extent such a teaching sequence would impact on student conceptual understanding of kinematic relationships. The teaching sequence took the form of a tutorial, which allowed interaction with and between students and discussion on the content of the teaching sequence. The evidence obtained in this iteration indicated that the teaching sequence on an alternative approach to acceleration as the net force to mass ratio did indeed enhance the student conceptual understanding of the acceleration of an object. This evidence links to the results obtained in previous iterations of the research study showing that explaining conditional statements and clarifying the consequences of such statements contribute to student conceptual understanding. Research on the effect of introducing comparative proportional reasoning (called qualitative reasoning) to undergraduate first-year physics students is continuing as a project in collaboration with two other universities in South Africa. The results relating to qualitative reasoning are therefore not included in this thesis.

3.5.2.5 Fifth iteration – Simplification: When is it reasonable to ignore the effect of air resistance

The result of the fourth iteration made it clear that it was useful to help students understand what the condition for free fall embodied and what the consequences were when one ignored air resistance with specific falling bodies. The more detailed research question for this iteration was:

What are the circumstances under which it is realistic to ignore the effect of air resistance on falling bodies. This emerged as a logical consequence of the recurrent demonstration in every iteration of the DBR of the difficulties arising from neglecting the effect of air resistance. Rather than a further experimental iteration, a computer code was developed to enable graphing of the actual speed for different falling objects at various points in a fall. A computer simulation then could model the motion of falling objects, both in the presence and in the absence of air resistance. The simulation allowed me to determine the influence of factors such as the height of fall, the mass and cross-sectional area of the falling objects and the air density on the motion of falling bodies. The details of this iteration are given in Chapter 8, which also includes a published paper on the iteration (Ferreira, Seyffert *et al.*, 2017).

3.6 Research instruments and data collection

The research instruments and methods used for data collection in each iteration, for example the revised versions of the questionnaire used in the grounding phase, various worksheets and student reflections, are described in detail in the relevant chapter about that iteration. Figure 3-3 summarizes the methods, sampling, data collection and analysis and the results for the various iterations.

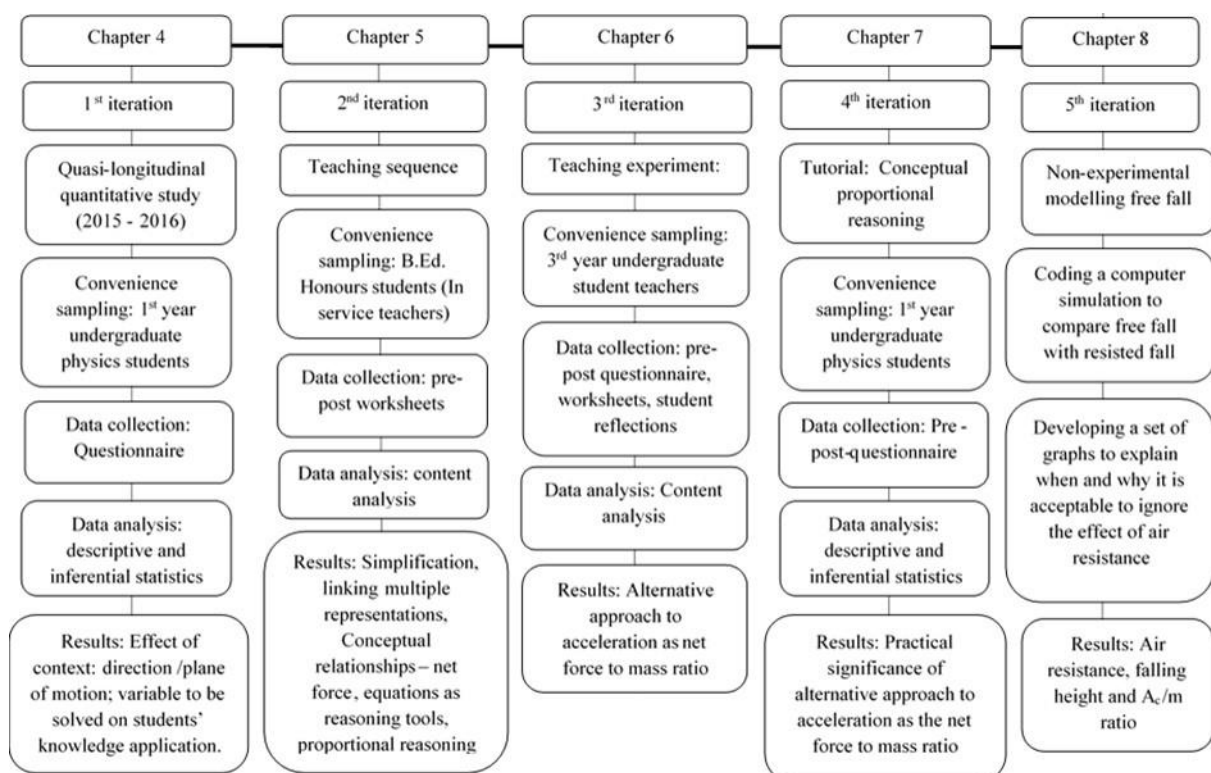


Figure 3-3: Methods, sampling, data collection and analysis for iterations

3.6.1 Data analysis

In this section I describe the different inferential statistics that were used to analyse and interpret the data.

3.6.2 Reliability of research instruments

Both Cronbach's Alpha and the mean inter-item correlation were calculated for each of the different versions of the questionnaire, to determine the reliability, or internal consistency, of the research instrument. The reliability of a measurement refers to the extent to which it measures a concept in a set of test items consistently. Cronbach's Alpha is a way of measuring the strength of that consistency. Inter-item correlations show the extent to which scores on one item are related to scores on all other items in a set of test items. In Table 3-2 below the respective values for the two statistics for the different versions of the questionnaire are summarized.

Table 3-2: Cronbach's Alpha and mean inter-item correlations for research instruments used in this research project

Phase of DBR	Questionnaire used in	Cronbach's alpha	Mean inter-item correlation
Grounding	Identification of problem	0.726	0.158
Iteration 1	Extent of problem	0.837	0.364
Iteration 4	Effect of alternative approach	0.798	0.327

The internal consistency of all three versions of the questionnaire is relatively high. For each one the Cronbach's Alpha reliability coefficient is more than 0.70, the value that is commonly accepted as indicating acceptable reliability. For the questionnaire used in determining the extent of the problem, the grounding phase, and for the questionnaire used in the third iteration, the mean inter-item correlations are both between 0.20 and 0.40, indicating that while the items are reasonably homogenous, they vary sufficiently so as to not be isomorphic with each other.

3.6.3 Inferential statistics used in data interpretation

Inferential statistics were used to determine the influence of the conceptual approach to acceleration on student understanding of acceleration. Chi-square tests compare the expected and actual distribution of data across categories. Cramer's V, denoted by ϕ_c , is based on adjusting chi-square significances to factor out sample size. Relationships between two groups are often given in terms of the p -value, the calculated probability. If the p -value is less than 0.05, the relationship between the two groups is sufficiently unlikely to be due to chance that by convention we conclude that a statistically significant relationship exists between two groups that are compared. Cramer's V was used in conjunction with the p -value to evaluate the strength of the relationship between the trends of responses regarding student conceptual understanding. To indicate whether the differences or agreement are practically significant the following guidelines apply: a value for Cramer's V of 0.1 means small practical significance, a value of 0.3 means that the comparison indicates medium practical significance and a value of 0.5 means large practical significance.

Cohen's d is an effect size used to indicate the standardised difference between two means or percentages (i.e. in an unpaired situation), to indicate the significance of the difference in the means of the pre-and post-intervention test results. The guidelines for interpreting Cohen's d (d) are that 0.2 indicates a small effect, 0.5 a medium effect and 0.7 a large effect.

3.6.4 Research ethics and codes of practice

The research procedures adhered to all the ethical requirements and codes of practice of the North-West University. The Ethical Clearance certificate (number NWU-00053-14-A3) is included as Appendix N. An example of the document of informed consent that the students completed for each iteration of the study is included as Appendix O.

3.7 Conclusion

In this chapter I have described the characteristics of DBR and justified its use in this study. I have also shown that each iteration emerged as a logical consequence of the previous iteration[s], explained how the various phases of a DBR study have been applied in the research and arguments advanced to justify the appropriateness of the samples used for the different iterations.

In the chapters to follow, Chapters 4 to 7, the details of the different iterations are given. In each chapter the rationale for the iteration, the method and research instruments used, sampling, data collection, data analyses and results are presented, together with the discussion of the results.

CHAPTER 4: ITERATION 1 - EXPLORING THE EXTENT OF THE RESEARCH PROBLEM

4.1 Introduction

The identification of the problem which informed this study resulted from my Master's study (Ferreira, 2014). The Master's study concerned objects in free fall, i.e. objects for which it was assumed gravitational force was the only force acting on the objects. The conditions of the absence of air resistance and friction opposing motion along non-horizontal planes were clearly stated in each item of the questionnaire from which the data for the Master's study were obtained. The main problem identified in those data was the difficulties caused by the alternative conception that 'heavier objects fall faster'. The results of the multiple choice items revealed various interesting trends in students' thinking. For example, it was shown that the direction of motion not only served to reveal student alternative conceptions but had a practically significant influence on students' choice of either the correct option or the option that indicated that heavy objects fall faster. The results showed that students did not apply the concept of free fall consistently across each of vertical motion up, vertical motion down, and motion on an inclined plane. The physics variable to be solved for in an item also had an influence on the option chosen for each item: items requiring comparison of the time of the falling objects had a higher percentage correct response than items where other variables were required, e.g. speed or distance. The study was described and results reported in a paper published in the proceedings of the European Science Education Research Association 2015 conference; this paper is reproduced in Appendix A.

The investigation of the Master's study informed the current research. As a Physical Sciences teacher for more than 30 years I was familiar with the difficulties learners experience with regard to force and acceleration. Becoming aware of the extent of the inadequacies in student understanding informed my desire to develop material that could be useful for teachers to teach the fundamental concepts so as to enhance understanding of introductory physics. To determine the extent of the effect of the direction of motion and the physics variable to be solved, the research was replicated in two consecutive years as the first iteration in this Design-Based Research study. The results of the first iteration initiated attempts to find ways to clarify and explain the use and effect of conditional statements in the teaching and learning of physics and enhance conceptual understanding of physics concepts relevant to accelerated motion.

4.2 Identification of the problem

Physics laws and definitions that are taught in introductory mechanics often contain conditional statements as an attempt to simplify the teaching and learning of physics. The influence of

inclusion of conditional statements is discussed in Chapter 2 section 2.6.2. Although the use of conditional statements serves to simplify the teaching of physics, and the accompanying mathematics, such simplification often increases the complexities associated with learning the physics (and the accompanying mathematics). For example, students tend to think that physics principles only apply to certain situations and are not related to their daily experience. Sometimes the condition to simplify an everyday situation is given by implication only, for example the phrase “free fall” implies motion is to be considered as solely under the influence of the force of gravity. By implication, the phrase free fall means that all forces other than gravitational attraction, such as air resistance, must be ignored, with the consequent implication that the relevant object will be subjected to gravitational acceleration.

It is the difficulties caused by conditional statements that are intended to simplify real world situations, and the learning consequences of such simplifications, that initiated the investigation reported here. The statements “ignoring the effect of air resistance” or “in the absence of air resistance” and their contributions to student alternative conceptions regarding free falling objects (motion under gravity) were of particular interest. Specifically, my interest in the effect of the condition of the absence of air resistance was raised when I noticed unexpected trends in student responses while conducting my Master’s study. After interviewing selected students, I realized that the condition of “ignoring the effect of air resistance” had a major impact on the way students interpreted questions on bodies moving under gravity, which then informed the current research. The findings informed the research question for this first iteration namely, to what extent does changing the physics context of questions on linear motion under influence of gravity only influence student responses to paired comparable questions?

4.3 First iteration of the DBR

In agreement with design principle 1 (the constructivist approach, p. 50), the prevalence of the alternative conception that heavier objects fall faster was investigated with two further groups of introductory undergraduate first-year physics students in a quasi-longitudinal study. For the first of these additional groups of students the questionnaire from the Master’s study was slightly changed by omitting certain questions. The questions that were omitted concerned horizontal motion which was outside the scope for the doctoral study and hence not applicable to a questionnaire on motion under gravity. The questionnaire was replicated again for the second group. The results that were obtained for the three versions of the questionnaire (my Master’s study and the two groups in this first iteration of the DBR) were consistent across the three data cohorts.

The results of the three groups of participants were summarized in separate frequency tables indicating the correct answers as well as the answers that indicated the alternative conception of heavier objects falling faster. Inferential statistics were used to compare the year groups for differences in responses and to determine the practical significance of observed trends. The McNemar test statistic (indicating the practical significance for differences between the data) as well as the phi-coefficient (which indicates the practical significance for correlations between paired items) was calculated from 2 x 2 contingency tables.

The extent to which changing the direction of motion and/or the variable to be solved revealed the existence of the alternative conception in student responses and its influence on student responses, made me realize that alternative conceptions could be used to advance teaching aimed at conceptual understanding. By identifying the existence of alternative conceptions, teachers can use those alternative conceptions to enhance their teaching. For example, by showing mathematically that the same principles apply to different context, e.g. different directions/planes of motion or different variables to be solved, coherence of physics principles could be emphasized. The details, collective results and inferences of the first iteration of the DBR is reported in a paper published by the journal Research in Science Education 2017 (doi: 10.1007/s11165-017-9638-y). The manuscript is reproduced in Section 4.6. Figure 4-1 is a diagrammatic description of the sequence of the initial research and the quasi-longitudinal study that informed the research problem.

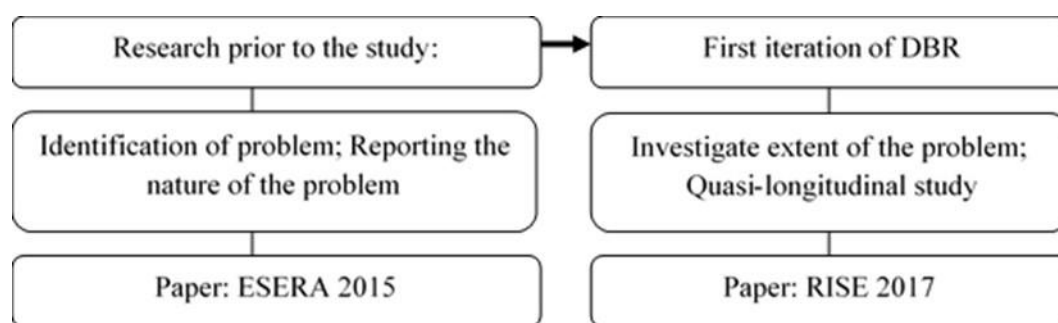


Figure 4-1: Sequence of research that informed the research problem

4.4 Progression of research informed by the first iteration of the study

The results described in the two published papers, as already noted one reproduced as Appendix A to the thesis and the other in this chapter, informed the design and development of [a] possible solution[s] to address the influence of student alternative conceptions regarding falling objects. Guided by the literature and based on my experience as a teacher, I realized that merely presenting mathematical evidence for a claim that the same physics principles applied to non-horizontal motion in different directions was not enough to develop and/or enhance student

conceptual understanding. Therefore, I purposefully designed a teaching sequence that included an explanation on conditional statements using a combination of representations to merge their affordances and introducing equations as reasoning tools. Figure 4-2 shows the progression of the research from the first iteration, as reported here (Chapter 4), into the second of the iterations, reported in Chapter 5, in which possible solutions to address the problem are designed, developed and tested.

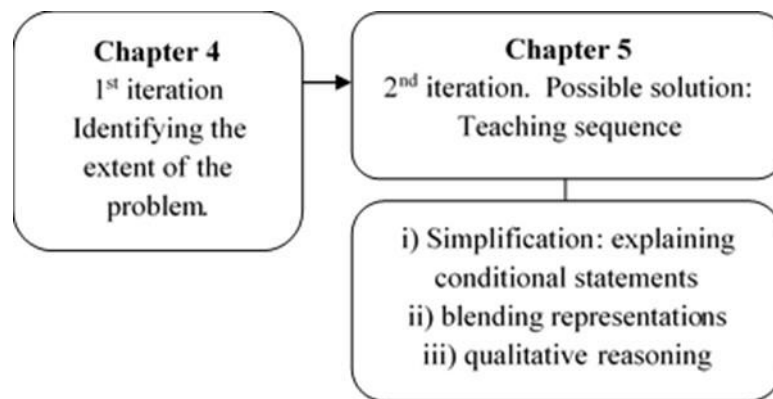


Figure 4-2: Progression of research informed by the first iteration

4.5 Conclusion

In Chapter 4 the research problem is described, namely the effect that conditional statements, in particular ignoring air resistance, have on student understanding. The detailed questions that guided each one of the subsequent iterations emerged as a result of a consistent focus on the fundamental research question: What circumstances will foster better understanding of specific physics relationships and concepts that are poorly understood? The circumstance specifically identified in this iteration that seemed to impede student conceptual understanding was non-explanation of the use and implications of conditional statements. The individual iterations in the present study are aimed at specific issues in an attempt to produce an approach that would enhance understanding of conceptual relationships in the domain of introductory mechanics. In the next chapter, Chapter 5, the implementation of a teaching sequence as a possible solution to address the alternative conception and thus enhance conceptual understanding of the threshold concept of gravitational acceleration, is described.

4.6 Article published in Research in Science Education: Alternative conceptions: Turning adversity into advantage

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Alternative Conceptions: Turning Adversity into Advantage

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Abstract While a vast body of research has identified difficulties in students' understanding about forces and acceleration and their related alternative conceptions, far less research suggests ways to *use* students' alternative conceptions to enhance conceptual understanding of a specific fundamental concept. This study focused on distinguishing between students' conceptual understanding of the Newtonian concept of gravitational acceleration being the same for all objects and students' alternative conception that heavy objects fall faster. A multiple choice questionnaire was distributed to first year physics students for three consecutive years at a university in South Africa. The results indicate that changing the direction of motion and the physics quantity asked in paired questions revealed practically significant inconsistencies in students' reasoning and conceptions. This research contributes to the body of knowledge in proposing how the alternative conception of mass-related gravitational acceleration can be used in instruction to enhance conceptual understanding of the force–mass–acceleration relationship. Understanding of this relationship not only promotes conceptual understanding of the basic Newtonian concepts of the laws of motion which forms the critical foundation on which more advanced physics courses are built, but also contributes towards students' perception of physics as a set of coherent ideas applicable in all contexts.

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Keywords Alternative conceptions · Conceptual understanding · Force and acceleration · Direction of motion · Threshold concepts

Introduction

Despite the recognized importance of the development of conceptual understanding and the existence of a huge body of empirical research on students' conceptions (see for example three extensive reviews of this and related research in Driver and Erickson 1983; Gilbert and Watts 1983; Duit et al. 2014), research in physics education shows that few students are able to explain daily events from a scientific point of view (e.g. Muis and Gierus 2014; Von Aufschnaiter and Rogge 2015). Conceptual understanding of the fundamental principles of motion and force and the ability to apply these Newtonian concepts in introductory mechanics courses are not only required to explain and predict everyday occurrences but are essential for laying the foundation for advanced physics and engineering courses (Hedge and Meera 2012; Williamson et al. 2016).

Empirical studies all over the world have reported and confirmed students' conflicting ideas on force and motion to such an extent that these ideas are referred to as the "body of intuitive mechanics" (Duit et al. 2014, p 446). The relationship between force, mass and acceleration as represented in Newton's second Law, $F = ma$, is probably the best known equation in school physics. However, the substantial body of previous and ongoing research on this topic indicates that a deep understanding of the relationship remains difficult. It is extremely common that students in introductory physics can apply the equations that express Newton's law without letting go of a fundamentally Aristotelian view of the relationships between force and motion (Kavanagh and Sneider 2007; Palmer 2001; Wilson et al. 2010). Because the concept of gravity in terms of Newton's second law is applied in various topics of introductory mechanics, e.g. projectile motions, weight forces, conservation of energy and conservation of momentum (Duit et al. 2014; Williamson et al. 2016), it is essential that the fundamental gravitational force–mass–acceleration relationship should be understood.

The Issues that Underpin This Study

The Epistemologies of Physics Students

Every student in introductory physics has a system of beliefs about physics unconsciously based on their everyday-life observations and experiences and their beliefs about physics (examples of reviews of relevant research are found in Duit et al. 2014; Ledermann and Ledermann 2014). Students' epistemologies of physics (i.e. their perceptions of the nature of physics knowledge in particular) affect many aspects of their physics learning, including their reasoning about physical situations (Chu et al. 2008; Duit et al. 2014; Muis and Gierus 2014; Von Aufschnaiter and Rogge 2015) and the extent to which they are willing to recognize, evaluate and reconstruct those ideas (Gunstone 1992). Although cognitive and affective issues are closely linked in conceptual change (Amin et al. 2014; Duit and Treagust 2003; Gunstone 1992), this linkage is not pursued further in this review. Many studies have reported that students' conceptual development is related to both their cognitive understanding of individual physics concepts and their epistemological beliefs about physics (e.g. Chu et al. 2008; Chu and Treagust 2014; Duit et al. 2014). Students' epistemological

frameworks vary from beliefs that knowledge consists of incontrovertible absolute truths—i.e. isolated facts that are fixed—to sophisticated beliefs that knowledge is subject to change, consists of coherent, interrelated ideas and involves the invention of explanations (Amin et al. 2014; Ledermann and Ledermann 2014). Some students' perceptions of physics as a set of disconnected facts and formulae, and of physics learning as absorption of information, contribute to their difficulty to apply concepts and principles to explain phenomena and solve problems to make sense of the natural world (Ledermann and Ledermann 2014). Responses like "It is common sense", "according to Galileo", "the textbook states" and "experts say that" point towards a naïve, unsophisticated physics framework, founded on external authority. Even though physics is based on only a small number of concepts, many students fail to see physics knowledge as a coherent structure (Duschl et al. 2011). When students are able to understand and use the underlying physics concepts, and when they know where and when specific concepts apply, they are able to solve problems, see physics knowledge as a coherent web of ideas which applies to all walks of life, and predict and explain various phenomena scientifically (Amin et al. 2014; Muis and Gierus 2014).

Alternative Conceptions

A substantial amount of research shows that every student enters introductory physics with a system of knowledge and beliefs about physics as a result of their repeated daily experiences in their everyday world (see the extensive bibliography in Duit 2004). The term alternative conception as used by Gunstone (1987) and Treagust (2012) is used in this paper to describe such pre-existing knowledge structures that contrast with formal physics concepts. This knowledge gained through experience is often transformed into intuitive rules and explicit conceptions (Amin et al. 2014; Von Aufschnaiter and Rogge 2015). The resulting knowledge structure is commonly very stable and activated by the student in a wide variety of contexts. We have known for over 35 years that this experiential knowledge system is extremely resistant to change and that it is commonly in serious conflict with accepted scientific knowledge, i.e. the fundamental principles to be learned in physics classrooms (Champagne et al. 1982; Duit et al. 2014; Von Aufschnaiter and Rogge 2015). Notions such as "a bigger weight will cause a bigger acceleration", "Gravity exerts the same force on all objects no matter what their weight" and "heavier objects fall faster" have been widely reported for over 35 years (see two extensive reviews of this and related research in Driver and Erickson 1983; Gilbert and Watts 1983).

Nature of Physics Knowledge/ Simplification

The high level of conceptual abstraction and the predominant role of mathematics which distinguish Physics from much of the other natural sciences may be responsible for certain teaching and learning difficulties (Duit et al. 2014). Because real-world phenomena are influenced by multiple and complex variables which require advanced physics for prediction and mathematics for measurement of those phenomena, the knowledge to be taught is often *manipulated* for Physics teaching. Real-world phenomena are idealized or *cleaned of distracting factors*, when introduced to high school or undergraduate students (Champagne et al. 1982; Duit et al. 2014). The physics of falling objects as taught in schools, for example, differs from everyday life in the sense that the situations taken from real life and used as examples to explain the concept of gravitational acceleration are almost always idealized—that is, stripped of all opposing frictional forces, e.g. such as air resistance.

There are excellent reasons relating to student learning for the simplification of the content structure to be the focus of instruction, but this must also be enriched by embedding the structure in contexts that make sense for the learners. For example, many students know the Newtonian simplification that objects released from the same height at the same time experience equal acceleration and therefore will reach the ground at the same time. When students have to apply the same concept (i.e. free fall) for the objects projected upward against gravity, however, they are unable to do so correctly (Ferreira and Lemmer 2015). Contrary to expectation, simplifying the conditions for falling bodies to free fall does not always simplify the problem. Students' lack of awareness of the differences between everyday life and the simplified idealized science contexts used in physics results in failure to resolve discrepancies between experiential observations and idealized physics explanations (Ferreira and Lemmer 2015; Gunstone and White 1981). This failure leads to a belief that science applies only to special situations, thus hindering the development of students' perception of physics as a coherent body of knowledge (Muis and Gierus 2014; Von Aufschnaiter and Rogge 2015). Reconstructing certain aspects of everyday experiences under theoretical perspectives forms the basis of physics thinking (Duit et al. 2014); therefore, the inability to do so contributes to student difficulties to develop understanding of physics concepts and the ability to use that understanding to solve physics problems.

Gravity as Threshold Concept

In all disciplines, there are certain concepts that students need to understand to develop conceptual understanding in a domain; these are usually labelled threshold concepts (Meyer and Land 2005). However, some of these concepts have proven to be exceptionally difficult to understand. Incomplete understanding of such threshold concepts is likely to have long-term effects on students' learning and their ability to apply their knowledge in new contexts; conversely, students who gain understanding of a threshold concept obtain "a transformed internal view of subject matter and subject landscape" (Meyer and Land 2005 p.373). A variety of threshold concepts in Physics have been identified (Perkins 1999; Psycharis 2016; Wilson et al. 2010), of which the concepts of force, acceleration, and gravity are of concern in this study. According to Williamson et al. (2016), students' understanding of gravity is closely related to their understanding of other physical concepts; therefore, students' understanding of gravity can serve as indication of student's understanding of other general physical concepts such as momentum and kinematics. The concept of the force–mass–acceleration relationship as it applies to objects moving in a gravitational field is applicable within the context of projectile and circular (planetary) motions as well as the conservation of energy and momentum.

Ferreira and Lemmer (2015) reported inconsistencies in students' understanding of the force–mass–acceleration relationship as students tended to choose the Newtonian concept of equal gravitational acceleration for objects in vertical downward free fall, but reverted to their alternative conception that heavy objects fall faster for vertical upward motion, i.e. against gravity. This is consistent with Wilson et al. (2010) report that students could apply the mathematical expression of Newton's second law but still embraced a fundamentally Aristotelian view of the relationship between force and motion. Such inconsistencies suggest students' lack of understanding of the force–mass relationship in the context of motion in a gravitational field.

Influence of Context

Evidence of the context dependence of students' alternative beliefs highlights the vital role that context plays in the physics learning process (Ferreira and Lemmer 2015; Gunstone and White 1981; Muis and Gierus 2014). For example, when confronted by contextual problems—problems in an everyday context—most students rely on their pre-instruction epistemic beliefs which suggests that specific patterns in students' reasoning are activated by the context of problems (Hedge and Meera 2012; Rebello and Rebello 2011; Amin et al. 2014). Distinctive characteristics of words used in the problem statement, i.e. surface features such as friction, inclined plane, often cue the recalling of specific thinking that discourages understanding of physics concepts. Novice students are much more likely to identify such surface features of a problem situation while, in contrast, experts focus on the underlying physics principle[s] involved, the deep structure—the fundamental principle not always specifically mentioned in the problem statement (Champagne et al. 1982; Serway and Jewett 2012). For example, some studies report that student reasoning for different problems involving the same direction or plane was consistent, while inconsistencies in their reasoning were noticed when vertical, horizontal and motion along an inclined plane—still all linear motion and so in terms of physics principles the same—were compared (Ferreira and Lemmer 2015; Palmer 2001; Lemmer 2013).

Information on the influence of the direction or plane of motion as separate contexts in student applications of kinematics concepts is limited. Research on students' applications of alternative conceptions of force–acceleration–motion relationships, however, has revealed that the direction and plane of motion play a role in student reasoning (Kavanagh and Sneider 2007; Lemmer 2013; Palmer 2001). Palmer (2001) reported on students' perception that gravity acts on objects moving vertically downwards but not on objects projected vertically upwards. One study reported on learners' perception of the direction of force of gravity on objects in vertical upward motion (Kavanagh and Sneider 2007), but none was found on the influence of the direction of vertical motion or variable to be solved on student application of general physics concepts. Lemmer (2013) presented evidence that student reasoning was consistent for the same type of motion, e.g. in a horizontal plane or motion in a vertical downward plane, but that the reasoning of the same students was inconsistent for motion both up and down an inclined plane as well as for motion against gravity.

The Impact—or Lack Thereof—of Conventional Teaching

Reports on students' tendency to revert to their alternative conceptions about basic physics ideas in situations outside the context where they learn specific physics concepts (e.g. Duit 2009; Von Aufschnaiter and Rogge 2015) show traditional tuition's failure to address and change alternative conceptions. These reports also support Treagust's (2012) argument that alternative conceptions that are not challenged become integrated into students' cognitive structures. As a consequence, students experience difficulty in integrating new information into what they already know resulting in incorrect understanding of the new concept (Treagust 2012).

Traditionally, physics education research was content-specific, evaluating students' knowledge about a specific topic. Students' capability to give Newtonian responses without Newtonian reasoning in regularly used multiple choice questions, however, lead to overestimation of the level of correct knowledge and assumption of conceptual understanding of concepts

(Palmer 2001). As educational researchers in various countries report deficiencies in introductory university physics students' ability to apply their physics knowledge in new contexts, it is clear that conventional tuition hardly promotes conceptual understanding of physics principles (e.g. Gunstone and White 1981; McDermott 1984; Von Aufschnaiter and Rogge 2015). Students' poor performance on problems set in real-world context highlighted conventional instruction's failure to identify or address ineffective tuition practises, and the need to develop tools that differentiate between students' conceptual knowledge and conceptual understanding (Muis and Gierus 2014; Rebello and Rebello 2011).

Diagnosing Alternative Conceptions and Enhancing *Conceptual Understanding*

Researchers' progress in understanding the nature and content of student conceptions and the process of conceptual change informed the design of more effective instruction (Amin et al. 2014). The large body of research on alternative conceptions mostly report on the difficulties these conceptions cause. Amin et al. (2014), however, argued that understanding the content and nature of student conceptions can contribute to student learning. Unfortunately, the majority of teachers do not effectively diagnose students' learning problems (Treagust 1995). Although various formative and summative assessment methods to obtain information on student learning are available, most of the methods are time consuming and consequently impractical for teachers to use (Treagust 2012). However, once obstacles in the way of student understanding are identified, students' learning needs can be addressed by incorporating specifically designed instruction procedures consistent with constructivist teaching approaches (Amin et al. 2014; Treagust 1995).

Various researchers argue that the main goal of an introductory physics course should be to help students to successfully develop both a good understanding of physics concepts and the ability to use that understanding to solve physics problems (e.g. Duit et al. 2014; Muis and Gierus 2014; Von Aufschnaiter and Rogge 2015). Studies of the influence of problem-context have evolved to allow evaluation of students' concept development and their level of conceptual understanding (Stewart et al. 2007) via diagnostic tests, for example the Force Concept Inventory (FCI) (Hestenes et al. 1992). The value of the FCI as instrument for analysing students' understanding of the concepts on force and motion has been established over many years (Treagust 1995). The sets of multiple-choice answers for each item containing distractors that address specific alternative conceptions designed to discriminate between Newtonian and non-Newtonian responses. Redish (2005) pointed out that while the FCI concept test is designed to indicate how well the students know the concepts, it does not indicate how well students can apply the concepts in problem solving.

The use and comparison of Elby pairs provide a simple and useful way to address this issue. Elby pairs are paired questions consisting of a question which most students are likely to answer correctly and another question in which students will likely fall back on their naïve knowledge while applying the same concept (Dreyfus et al. 2014; Redish 2005). By comparing the way in which students applied the same concept in different situations, inconsistencies in their reasoning are revealed. The concept of Elby pairs corresponds with the proposal by Minstrell (1982) to juxtapose alternative conceptions with physics concepts, and thereby reveal the existence and nature of student alternative conceptions and the reasoning behind naïve (experiential) knowledge (Minstrell 1982; Muis and Gierus 2014). The revealed inconsistencies in student reasoning create cognitive conflict (Johnson and Johnson 2009; Von

Aufschnaiter and Rogge 2015), and when students are encouraged to attempt to resolve the cognitive conflict, they will be more likely to learn to think about coherence and to evaluate and refine their intuitions (Gunstone; private communication 2016).

Different views exist on the instructional implications of alternative conceptions. Initially, the disagreement was on whether student conceptions should be replaced by or whether it should be transformed into scientific conceptions (Amin et al. 2014). Duschl et al. (2011) argued that exposure to new information does not automatically mean that the information is understood and integrated into students' existing knowledge. Attempts to replace or amend students' alternative conceptions with the acceptable conceptions via direct instruction—the “fix it” (Duschl et al. 2011) or “replacement” approach (Driver and Erickson 1983 as cited in Amin et al. 2014)—do not contribute to reorganization of knowledge which is required for change. To address students' alternative conceptions, a multiple conceptual change view that includes conceptual changes on the fundamental level of concepts and principles will be required (Duit et al. 2014).

In contrast with the replacement approach, the intuition-based “Work with it” (Duschl et al. 2011) view uses students' intuitive ideas or perspectives as starting points to design more effective instruction. This view corresponds with the transformation view of Osborne and Freyberg (1985 as cited in Amin et al. 2014, p. 60) which ‘promoted capitalising on students' ideas rather than confronting them’. Gravity for example is a concept that everyone has daily experience with and is therefore an excellent starting point for identifying and reshaping students' alternative conceptions (Williamson et al. 2016). While many students give the Newtonian response that objects under the influence of gravity move with equal (gravitational) acceleration for vertically downward motion, the persistence of the alternative conception that heavy objects fall faster is revealed in responses to problems of motion against gravity (Lemmer 2013; Ferreira and Lemmer 2015). With the ‘Work with it’ view, students are asked to evaluate and refine their alternative ideas in order to be aligned with the scientifically correct conceptions. Such refinements can contribute to students' development of epistemological understanding. The connection between epistemological sophistication and conceptual change had been established by a convincing body of research (Amin et al. 2014); therefore, a new reason for developing epistemological understanding emerged, to promote conceptual understanding itself (Amin et al. 2014).

The “work with it” view also meets the requirements of three broad types of conceptual change identified by Driver et al. (1994) (cited in Duschl et al. 2011, p 14) and Amin et al. (2014) namely reflecting on their alternative ideas, developing shared norms and epistemological standards to discuss and evaluate their ideas and work to solve anomalies or inconsistencies between alternative and scientific conceptions by restructuring a network of concepts. Recognizing their inconsistent reasoning from the responses on Elby pairs for example, reflecting on their alternative responses and discussing the responses to paired questions in instruction-assisted interventions, creates *teachable moments* (our term) to help the students to reconcile the two responses. When students recognize how their alternative ideas need to be refined in order to be aligned with the scientifically correct assumptions, new levels of explanation are achieved (Duschl et al. 2011).

Although cognitive and affective issues are closely linked in conceptual change (Duit and Treagust 2003), the nature of this research did not allow inclusion of the affective measures involved in conceptual change; therefore, exclusion of this aspect does not indicate its unimportance.

Research Questions

The main question this research attempted to answer was as follows: to what extent does changing the physics context of questions on linear motion under influence of gravity only influence student responses to paired comparable questions? In order to obtain realistic, reliable and valid answers, the following secondary questions were asked:

- (1). What information regarding students' conceptual understanding and pre-existing conceptions is revealed by changing the physics contexts?
- (2). How can the acquired information be implemented in tuition to advance coherent conceptual understanding?

Research Design

Research Population

The investigation was a large-scale quantitative study for three consecutive years involving students enrolled for first-year physics at the North–West University, South Africa, a total of 1826 students. The students were enrolled for either the calculus-based module, compulsory for engineering students and for students who enrolled for Physics as a major, or the non-calculus-based module, designed for students whose course requires physics at first-year level only. While it is required of all physics first year students to have passed Physical Science as a subject at grade 12 level, an additional minimum standard is required for engineering students. Table 1 presents demographic information about the research population for each year.

Methodology

A survey research design using questionnaires for quantitative data collection was chosen. The intent was to obtain longitudinal numeric data with statistical analysis for a quantitative description of trends. Three research experts in the field of teaching mechanics evaluated the questionnaire for content validity. The research complied with all the ethical requirements of the university and has formal approval from the relevant university committee.

Research Instruments

The Force Concept Inventory, the most widely used test to determine undergraduate students' ability to distinguish between correct Newtonian answers and alternative beliefs, provided the

Table 1 Demographic information of students across the 3 years

Year	<i>N</i>	% Female	% Male	% Calculus	% Non-calculus
2014	481	39	61	47	53
2015	664	34	66	61	39
2016	681	39	61	59	41
Total	1826	37	63	56	44

vehicle for investigation of the Newtonian concept of *Gravitation acceleration is independent of mass* versus the alternative *heavier objects fall faster* conception. Item 1 in the standardized Force Concept Inventory (FCI) (Hestenes et al. 1992) was useful for probing students' understanding of this concept (Treagust 2012; Redish 2003) while belief in the misconception (heavier objects fall faster) was suggested by selection of the corresponding option of item 1.

Data were obtained by administering questionnaires to each group of first year students for three consecutive years. A questionnaire was initially developed by the first author, reviewed by two academics in the field and administered to a group of first year physics students (Ferreira and Lemmer 2015). The results of the initial questionnaire informed the design and compilation of the successive questionnaires for the second and third iterations of the study. Five core items of the first iteration were duplicated in the successive iterations and the results compared to that of the initial study. Some of the items in the questionnaire were based on and variations of Item 1 of the Force Concept Inventory (FCI) by Hestenes et al. (1992) while the item on the inclined plane was informed by item 15 of The Energy and Momentum Concepts Survey by Singh and Rosengrant (2003).

The two major aspects considered in the process of designing the items were the physics quantity asked and the physical context (problem setting). The problem setting, from here on referred to as the physical context, had two sub-facets described here as follows: (1) superficial context (either a formal abstract or a contextual everyday situation) and (2) relevant context (referring to the direction or plane of motion—vertical or inclined plane). Four of the items involved items with zero initial velocity while the one item in upward vertical direction had non-zero initial velocity but zero final velocity. For all items, constant acceleration due to the force of gravity had to be inferred.

The physical context situation for each item is presented in Table 2.

All the items were set in an idealized theoretical context, i.e. students were instructed to ignore the effect of air resistance and other frictional forces. The items on linear motion were set in vertical upward, vertical downward directions as well as on inclined planes. None of the items required a mathematical solution. In each item, the motion of two objects had to be compared and the outcome predicted in terms of the physics quantity asked. In all items, the objects' masses differed but the other physics quantities (distance, velocity, time) were either given/implicit as being the same, could be deduced, or were asked. Since the linear motion in each item was one-dimensional only, the magnitudes of displacement and distance, velocity and speed of each object were the same. The term 'distance' was used to indicate how far the objects moved, whereas 'velocity' and 'speed' were both used in the questionnaire to indicate how fast the objects were moving. All items were verbal representations of the physical context.

Table 2 Physical context situations of items

	Item 1	Item 2	Item 3	Item 4	Item 5
Verbal description	Formal	Formal	Contextual	Contextual	Formal
Direction/plane	Vertical downward	Vertical downward	Inclined plane	Vertical downward	Vertical upward
Quantity asked	time	speed	speed	time	speed
Symbolic description	$F \downarrow t$	$F \downarrow v$	$C \swarrow v$	$C \downarrow t$	$F \uparrow v$

The topic of acceleration due to the force of gravity being independent of mass was chosen to investigate and compare students' understanding and application of Newton's second law (the relationship between the net force, mass and acceleration) in different directions and planes of motion. The underlying concept for all items was that when gravitational force was the only (and so net) force acting on the objects, the objects' accelerations would be equal, i.e. the (component of the) gravitational force/mass ratio. Because of the equal acceleration, the time-related change in either the objects' positions or velocities would also be the same. Each multiple-choice item had at least one distracter which would reveal the common alternative conception related to force/mass ratio, namely that 'heavier objects fall faster'. With this questionnaire, the researcher wanted to determine (i) to what extent the students applied this physics knowledge in comparable items when the direction of motion and/or the variable to be solved were changed and (ii) what information regarding students' conceptual understanding of the relationship between acceleration, the (component of) gravitational force and mass of an object was revealed.

Quantitative Data Analysis

Frequency tables showing the percentage of students who choose the correct options and the options that indicated the alternative conception were compiled and presented in table. Inferential statistical analysis was conducted to (i) compare the year groups for differences in responses and (ii) determine the practical significance of observed trends. The McNemar test statistic (ω) (effect size that indicates the practical significance of the differences found in data) as well as the phi-coefficients (indicating correlation between paired items) were calculated from 2×2 contingency tables in which the students' responses to paired items were compared. Table 4 contains the comparison of the students' responses as well as the test statistics of the paired items.

The inferential statistics for the questionnaire were obtained by using SPSS Statistics Version 22, Release 22.0.0. The effect size and the correlation coefficients were interpreted according to the guidelines provided by Cohen (1988), which suggest that effect sizes with values of $\omega < 0.3$ are considered small, $0.3 \leq \omega \leq 0.5$ medium and $\omega > 0.5$ large effects. Any relationship larger than 0.5 can be taken to be 'practically significant'. In this research, a large effect size for an item-pair is taken to mean that a practically significant number of students who answered one item correctly did not answer the other item correctly. A small effect size means that a practically significant number of students had either both items in an item-pair correct or both items wrong, i.e. the pair was generally answered in the same way.

Results and Discussion of Results of Empirical Study

Pairing the items allowed us to compare student responses to problems that differed in terms of the factors we investigated. The results of the study indicated that students' responses to comparable kinematics problems differed significantly when the directions/planes of motion and/or the physics quantity to be solved were changed. Comparing the frequencies of the chosen options for the items revealed students' lack of understanding of the relationship between the force of gravity, mass and acceleration and indicated that alternative conceptions persisted even after tuition of the topic of forces was completed.

Descriptive Statistics—a Broad Overview of the Data

The percentages of students who chose the correct option as well as the percentages that chose the option representing the alternative conception that *heavy objects fall faster* (here and for the remainder of the paper referred to as the *alternative conception*; other incorrect distractors are referred to for the remainder of the paper as ‘incorrect’), are presented in Table 3.

Figures 1 and 2 are visual representations of the results shown in Table 3; the % correct options are presented in Fig. 1 and the % alternative conceptions in Fig. 2.

Comparison of the two graphs showed that all three research groups revealed similar trends, with items 3 and 5 the common outliers. Items with lower percentages of correct options (Fig. 1) had higher percentages in the choice of the alternative conception (Fig. 2). Items 3 and 5 had the lowest percentage of correct responses and the highest percentage of alternative conceptions.

For the items set in downward motion, Fig. 1 shows that the correct responses to items 2 and 4 were nearly the same but lower than that of item 1. Item 1 had the most average correct responses across all 3 years 78%, with the average percentages of item 2 66% and item 4 63%. The alternative conceptions showed a trend inverse to that of the correct options. Figure 2 shows that the average percentages across all 3 years for the choice of alternative conceptions were relatively low for item 1, 19%, but the average percentages for items 2 and 4 increased to 28 and 30%, respectively.

Items 3 and 5 (both set in different direction/plane of motion) had the least percentage of correct responses and the highest percentage of alternative conceptions. The average percentage of the correct option across the 3 years for item 3 was 28% with the average percentage for the alternative conception 47%. For item 5, the average percentage of correct options across the 3 years was 37% while the average percentage for the alternative conception also was 47%. These results are discussed in more detail in the section on inferential statistics.

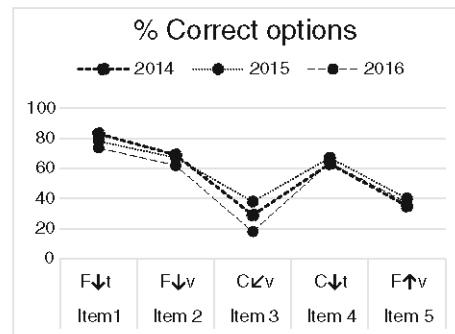
Inferential Statistics—a more Detailed Set of Data Analyses

Inferential statistical analysis was conducted to determine the practical significance of the observed differences or similarities. No practically significant differences between the year groups’ responses to individual items were found; in fact, corresponding trends in the responses were noted for the three groups. Students’ responses to individual items were compared to all other items, and the results of the comparison of all possible comparisons as well as the test statistics for the paired items are presented in Table 4. Each comparison of an

Table 3 Percentages of correct and alternative conceptions chosen for each item—descriptive statistics

Item	Context	Correct %				Alternative %			
		2014	2015	2016	Average	2014	2015	2016	Average
1	F↓t	84	78	73	78	15	20	23	19
2	F↓v	69	67	62	66	25	26	33	28
3	C↙v	29	38	18	28	48	51	66	47
4	C↓t	58	67	64	63	38	29	34	30
5	F↑v	35	40	37	37	52	51	51	47

Fig. 1 Percentage correct by item and by year



item pair is labelled with a letter ranging from ‘A’ to ‘J’ to allow easy reference in the subsequent discussion.

The term *Treatment Effects*—number of changes in the physics contexts of the paired items—is now briefly explained by means of a few examples. The context situation of item 2 ($F\downarrow v$) and item 4 varied from that of item 1 ($F\downarrow t$) in one aspect each. In item 2, the physics quantity to be solved differed as the students had to compare the speed of the objects instead of the time while the relevant physical context was kept the same. Items 1 ($F\downarrow t$) and 4 ($C\downarrow t$) differed in terms of the superficial context as item 4 was set in an everyday context using familiar objects, e.g. a teddy bear and a handbag instead of two balls, while the direction of motion and the physics variable asked were kept the same. The physical context in which item 5 was set ($F\uparrow v$) varied from that of item 1 ($F\downarrow t$) in two aspects namely the physics quantity asked and the direction of motion.

Interpretation of Table 4

We now consider the two matters in the data presented in Table 4 that are central to the research questions: first the different treatment effects (the number of changes in the physics contexts of the paired items) and second the effect of the change of contexts. The average percentages across the 3 years of data collection are used to simplify reporting and discussion of the results.

Fig. 2 Percentages answering ‘alternative conception’ [heavier falls faster] by item and by year

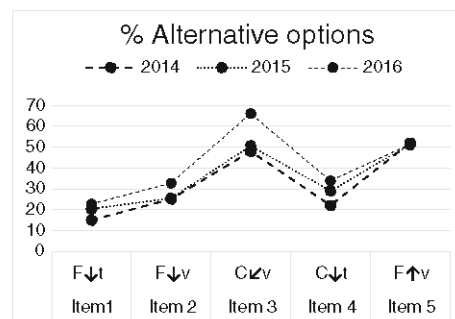


Table 4 Comparison of students' responses on paired items—inferential statistics

Comparison	Paired items	Context	Treatment Effects	Year	Paired Items					
					% both items x	% both items $\sqrt{}$	% item 1 $\sqrt{}$; item 2 x	% item 1 x; item 2 $\sqrt{}$	phi	Mc Nemar
A	1;2	$F\downarrow t$; $F\downarrow v$	1	2014	(1x; 2x)	(1 $\sqrt{}$; $\sqrt{}$)	(1 $\sqrt{}$; 2x)	(1x; 2 $\sqrt{}$)	θ	ω
				2015	86	80	21	14	0.52	0.35
				2016	80	81	20	20	0.54	0.23
				2016	83	78	22	17	0.55	0.25
				Av.	83	79	21	17	0.54	0.28
					(1x; 3x)	(1 $\sqrt{}$; 3 $\sqrt{}$)	(1 $\sqrt{}$; 3x)	(1x; 3 $\sqrt{}$)		
B	1;3	$F\downarrow t$; $C\swarrow v$	3	2014	91	33	67	9	0.19	0.72
				2015	84	44	56	16	0.25	0.58
				2016	93	22	78	7	0.17	0.72
				Av.	89	33	67	11	0.20	0.67
					(1x; 4x)	(1 $\sqrt{}$; 4 $\sqrt{}$)	(1 $\sqrt{}$; 4x)	(1x; 4 $\sqrt{}$)		
					88	74	27	12	0.47	0.41
C	1;4	$F\downarrow t$; $C\downarrow t$	1	2015	85	80	20	15	0.58	0.28
				2016	80	80	21	21	0.54	0.21
				Av.	84	78	22	16	0.53	0.30
					(1x; 5x)	(1 $\sqrt{}$; 5 $\sqrt{}$)	(1 $\sqrt{}$; 5x)	(1x; 5 $\sqrt{}$)		
				2014	78	37	63	22	0.12	0.65
				2015	80	45	55	20	0.22	0.55
D	1;5	$F\downarrow t$; $F\uparrow v$	2	2016	83	45	55	17	0.25	0.54
				Av.	80	42	58	20	0.20	0.58
					(2x; 3x)	(2 $\sqrt{}$; 3 $\sqrt{}$)	(2 $\sqrt{}$; 3x)	(2x; 3 $\sqrt{}$)		
				2014	89	37	63	11	0.26	0.58
				2015	86	49	51	14	0.34	0.47
				2016	91	23	74	9	0.18	0.61
E	2;3	$F\downarrow v$; $C\swarrow v$	2	Av.	88	37	62	12	0.26	0.55
					(2x; 4x)	(2 $\sqrt{}$; 4 $\sqrt{}$)	(2 $\sqrt{}$; 4x)	(2x; 4 $\sqrt{}$)		
				2014	64	76	24	36	0.39	0.01
				2015	64	80	20	36	0.43	0.03
				2016	60	79	21	39	0.40	0.04
				Av.	63	78	22	37	0.41	0.03
F	2;4	$F\downarrow v$; $C\downarrow t$	2		(2x; 5x)	(2 $\sqrt{}$; 5 $\sqrt{}$)	(2 $\sqrt{}$; 5x)	(2x; 5 $\sqrt{}$)		
				2014	75	39	61	26	0.13	0.48
				2015	79	48	52	21	0.26	0.42
				2016	82	49	51	18	0.31	0.40
				Av.	78	46	55	22	0.23	0.43
					(3x; 4x)	(3 $\sqrt{}$; 4 $\sqrt{}$)	(3 $\sqrt{}$; 4x)	(3x; 4 $\sqrt{}$)		
G	2;5	$F\downarrow v$; $F\uparrow v$	1	2014	45	84	16	55	0.27	0.52
				2015	44	81	19	56	0.25	0.43
				2016	41	87	13	59	0.23	0.65
				Av.	43	84	16	57	0.25	0.53
					(3x; 5x)	(3 $\sqrt{}$; 5 $\sqrt{}$)	(3 $\sqrt{}$; 5x)	(3x; 5 $\sqrt{}$)		
				2014	72	51	49	28	0.22	0.10
H	3;4	$C\swarrow v$; $C\downarrow t$	2	2015	70	56	44	30	0.26	0.03
				2016	68	64	36	31	0.25	0.34
I	3;5	$C\swarrow v$; $F\uparrow v$	2							

Table 4 (continued)

Comparison	Paired items	Context	Treatment Effects	Year	Paired Items					
					% both items x	% both items $\sqrt{}$	% item 1 $\sqrt{}$; item 2 x	% item 1 x; item 2 $\sqrt{}$	phi	Mc Nemar
J	4;5	C $\downarrow$ t; F $\uparrow$ v	3	Av.	70 (4x; 5x)	57 (4 $\sqrt{}$; 5 $\sqrt{}$)	43 (4 $\sqrt{}$; 5x)	30 (4x; 5 $\sqrt{}$)	0.24	0.16
				2014	78	43	58	22	0.21	0.43
				2015	81	50	50	19	0.30	0.41
				2016	80	47	53	20	0.27	0.42
				Av.	80	47	54	20	0.26	0.42

Treatment Effects; the number of changes in the physics contexts of the paired items

Meanings of symbols used: *F/C* superficial context—formal or every day; *w/t* physics quantity asked—time or velocity; *arrows* direction or plane of motion— $\downarrow$ vertical downwards; $\uparrow$ vertical upwards; $\sqrt{}$ inclined plane

Influences of Treatment Effects

These comparisons are considered in three groups: comparisons of items with one effect, then two effects and then three effects.

Items with one treatment effect:

Comparison A: item 1: item 2 (F $\downarrow$ t; F $\downarrow$ v); difference in physics quantity asked

The results indicate that the students answered the items in the same way; 79% of the students who had item 1 correct also answered item 2 correctly, while 83% of the students who answered item 1 incorrectly also answered item 2 incorrectly. Only 21% of students who had item 1 correct had item 2 wrong. The correlation between the paired items is high and is suggested by the Phi value to be practically significant ($\theta = 0.54$). The effect sizes for this item pair were small ($\omega = 0.28$).

Comparison C: Item1: item 4 (F $\downarrow$ t; C $\downarrow$ t) difference in superficial context; formal versus everyday context

This item pair showed similar results as the previous comparison. A total of 78% of students who had item 1 correct also had item 4 correct while 22% of the students who had item 1 correct, had item 4 wrong. The effect sizes were slightly higher at medium significance ($\omega = 0.3$) with the correlation practically significant at $\theta = 0.53$.

Comparison G: Item 2: item 5 (F $\downarrow$ v; F $\uparrow$ v) difference in direction of motion

The low correlation between this item pair ($\theta = 0.23$) is reflected in the comparison of answers to the items. Between 78% of students who had item 2 wrong also had item 5 wrong but only 46% of the students who had item 2 correct also answered item 5 correctly. The effect sizes ($\omega = 0.43$) indicate a medium practical significance of the difference in students' responses.

Items with two treatment effects:

Comparison D: Item 1; item 5 ($F\downarrow t$; $F\uparrow v$) different direction of motion and physical quantity asked

The effect sized for this pair was high ($\omega = 0.58$) indicating a practically significant difference in the way students answered the items. The correlation is low at $\theta = 0.2$. While 80% of the students who had item 1 wrong also had item 5 wrong, only 42% of the students who had item 1 correct also had item 5 correct. A total of 58% of students who answered item 1 correctly had item 5 wrong while 20% of students who had item 1 wrong had item 5 correct.

Comparison E: Item 2; item 3 ($F\downarrow v$; $C\swarrow v$) different superficial context and direction of motion

Of the students who answered item 2 correctly, 37% had item 3 correct while 62% answered item 3 wrong. A total of 88% of students who had item 1 wrong also had item 3 wrong. The phi coefficients were small, $\theta = 0.26$, i.e. low correlation. The difference between students' responses was high with practically significant effect sizes ($\omega = 0.55$).

Comparison F: item 2; item 4 ($F\downarrow v$; $C\downarrow t$) difference in superficial context and physics quantity asked

The medium correlations between these items ($\theta = 0.41$) indicate that the items were answered similarly. A total of 78% of the students who had item 2 correct also had item 4 correct and 62% of the students who answered item 2 wrong also answered item 4 wrong.

Comparison H: item 3; item 4 ($C\swarrow v$; $C\downarrow t$) difference in direction of motion and physics quantity asked

Of the students who answered item 3 correctly, 84% answered item 4 also correctly. However, 57% of the students who had item 3 wrong had item 4 correct. The effect sizes are practically significant ($\omega = 0.53$).

Comparison I: item 3; item 5 ($C\swarrow v$; $F\uparrow v$) difference in superficial context and direction of motion

The results of this comparison seemed inconclusive as both the items in this comparison were answered poorly in the questionnaires. The correlation between these items was small but so was the effect size. A total of 70% of students who answered item 3 wrong also answered item 5 wrong but 57% of students who had item 3 correct also had item 5 correct.

Items with three treatment effects:

Comparison B: item 1; item3 ($F\downarrow t$; $C\swarrow v$)

The correlation between these items was low, $\theta = 0.20$, and the effect sizes very high ($\omega = 0.67$). Only 33% of the students had both items correct, while 67% of students who answered item 1 correctly had item 3 wrong. A total of 89% of students who had item 1 wrong also had item 3 wrong.

Comparison J: item 4; item 5 ($C\downarrow t$; $F\uparrow v$)

The correlation coefficient between these two items was small to moderate ($\theta = 0.26$) while the effect sizes indicated moderate practical significance ($\omega = 0.42$). A total of 47% of the students who had item 4 correct also had item 5 correct while 54% of the students who had item 4 correct answered item 5 incorrectly.

Discussion of the Influence of Changes in the Context

The item pairs for which the correlations between responses were high and, as judged by the interpretations effect size described above, practically significant, were the pairs set in the same direction of motion (in this study vertical downwards; comparisons A, C and F). Changing the superficial context (formal/everyday context—comparison C) or the physics quantity asked (comparison A) appears to have only a very small influence on the way that the students responded to the items. Low correlations, the consequence of large differences in student answers for the item pairs, occurred where the direction of motion differed (comparisons B, D, E, G, H, J). The responses to the item pairs in these comparisons were examined more closely in terms of possible trends regarding the choice of the alternative conception that heavy objects fall faster, and the results of this detailed examination are presented in Table 5.

Item pairs for which the answers differed the most (and all with practically significant effect sizes) were those pairs where items were compared to item 1, especially where both the

Table 5 Changing the direction of motion and the impact on the alternative conception of acceleration of falling bodies?

Comparison	Paired items	Context	Year	1 ($a\downarrow$; b_x) %	2 ($a\downarrow$; b_{alt}) %	3 (b_x ; b_{alt}) %	4 (b_{alt} ; $a\downarrow$) %
B	1;3	$F\downarrow t$; $C\downarrow v$	2014	67	39	58	81
			2015	56	36	64	70
			2016	78	27	34	62
			Average	67	34	52	71
			2014	63	43	69	83
D	1;5	$F\downarrow t$; $F\uparrow v$	2015	55	36	67	71
			2016	55	23	42	68
			Average	58	34	59	74
			2014	63	30	48	63
			2015	51	29	56	56
E	2;3	$F\downarrow v$; $C\downarrow v$	2016	74	22	29	51
			Average	62	27	45	57
			2014	61	35	58	68
			2015	52	30	57	58
			2016	51	18	35	53
G	2;5	$F\downarrow v$; $F\uparrow v$	Average	55	28	50	60
			2014	39	27	69	56
			2015	35	30	86	59
			2016	48	23	48	53
			Average	41	27	68	56
H	4;3	$C\downarrow t$; $C\downarrow v$	2014	58	30	51	57
			2015	50	29	57	56
			2016	53	19	35	55
			Average	54	26	48	56
			2014	58	30	51	57

Column 1 (a_v; b_x) shows that 67% of students who had item 'a' correct had item 'b' incorrect. A total of 34% of students who had item 'a' correct chose the alternative conception for item 'b' (column 2; (a_v; b_{alt})). This means that 52% of the students who had item 'b' wrong chose the alternative conception (column 3). The last column indicates that 71% of students who choose the alternative conception in item 'b' chose the correct option for item 'a'.

Comparing the percentages in columns 2 and 4 for comparison B, only 34% of all the students who chose the correct option for item 1 also chose the alternative conception for item 3. However, 71% of the students who chose the alternative conception for item 3 made the correct choice for item 1—a difference of 37%. This means that a substantial percentage of students who chose the alternative conception in item 'b' chose the Newtonian correct option in item 'a'. This indicates that while some students who had item a correct had the alternative conception for item b, many students who chose the alternative conception for b originally chose the correct option for a; hence, the responses to item b are a better indication of the lack of conceptual understanding of the ratio between gravitational force and mass. The same trend is noticed for all the paired items. The differences in the values of columns 2 and 4 for comparisons E, G and J are slightly lower than for B and D; however, all the differences are between 30 and 40%.

Discussion of the Results of Changing the Direction of Motion and Revealing the Alternative Conception

The values in Table 3 show that for items 1, 2 and 4, more than 60% of the students gave the Newtonian option, that the objects experience equal acceleration in the absence of any opposing forces, i.e. when the force of gravity is the only (net) force acting on objects. Based on these results, we infer that the students know the concepts, at least at a superficial level. However, the inconsistency in students' responses (comparison of the values of column 2 and column 4) pointed towards a tendency to revert to their alternative belief when the physics contexts differed from the learned situation. We argue that when the physics contexts of direction of motion and physics quantity asked were changed, students' lack of conceptual understanding of the relationship between net force, mass and acceleration was exposed. This suggests that they did not, and likely could not, apply their knowledge to contexts that differed from the context in which they learned that knowledge. Hence, we propose that items in which the direction of motion and the physics quantity asked are changed from the learned situation are useful in elucidating students' lack of conceptual understanding of the relationship between gravitational force and mass, i.e. acceleration as the net force to mass ratio.

Conclusion

This study was designed and executed to investigate the extent to which different physics contexts revealed students' lack of conceptual understanding of acceleration as the net force to mass ratio for objects in non-horizontal motion. The research also investigated the correlation between students' choice of the Newtonian option in one item and the alternative conception option that *heavy objects fall faster* in another item. A number of conclusions can be drawn as a result of the findings.

Column 1 (a_v; b_x) shows that 67% of students who had item 'a' correct had item 'b' incorrect. A total of 34% of students who had item 'a' correct chose the alternative conception for item 'b' (column 2; (a_v; b_{alt})). This means that 52% of the students who had item 'b' wrong chose the alternative conception (column 3). The last column indicates that 71% of students who choose the alternative conception in item 'b' chose the correct option for item 'a'.

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With regard to the main research question, “To what extent does changing the physics context of items influence student responses to paired comparable questions?” the results indicated that the students’ responses to paired items differed significantly with specific changes in the physics context. While the differences between formal and everyday context were not significant for responses in this item set, the combination of changing the direction/plane of motion and the physics quantity asked resulted in significant differences in students’ responses to paired items. Items in which the physics quantity asked and/or the direction of motion differed from the generally used ‘compare the time for vertical downward motion’ revealed the students’ inconsistency in applying the Newtonian conception better than items set in the aforementioned context.

With respect to the second question: “What information regarding students’ conceptual understanding and pre-existing conceptions is revealed by changing the physics contexts?” we argue that students’ responses indicate a general failure to apply the net force to mass ratio in contexts that differ from what they were used to, which in turn points towards a lack of conceptual understanding. The consistency of the alternative conception that heavy objects fall faster as the alternative choice to the correct option supports this argument.

With respect to the third question: “How can the acquired information be implemented in tuition to advance conceptual understanding?” we argue that by changing the physics context of questions commonly asked during tuition, such questions can become instruments for diagnosing some of the detail of students’ lack of understandings. Rephrasing the questions allows students the opportunity to reflect on their understanding of the concept in different contexts, realizing their inability to either recognize or apply Newton’s second law in non-horizontal motion.

Implications

In addition to the diagnosis of inadequacies of understanding discussed above, this study has other implications. First, previous research over many years has consistently shown that students’ alternative conceptions are very hard to change. In mechanics in particular, these kinds of conceptions derive from everyday experiences students have which are generalized to intuitive rules and conceptions. Attempts to *fix* these alternative conceptions in conceptual change (the *misconception-based fix it view*) by merely telling students that objects fall at equal acceleration in the absence of air resistance do not help to change their conception (Duschl et al. 2011). Being asked to apply the concept in various contexts, however, has the clear potential to challenge students’ existing conceptual understanding as they explore specific phenomena in a greater variety of conceptual questions.

Presenting standard examples in an alternative context allows for an instruction-assisted intervention based on the intuition-based *Work with it* (Duschl et al. 2011) view of conceptual change instruction. By elucidating this alternative conception, the tentative nature of physics knowledge is illuminated which in turn contributes to developing epistemological understanding of physics. We certainly do not claim that this approach will change students’ epistemological beliefs or alternative conceptions. However, understanding the fundamental concept of acceleration as the net force to mass ratio is likely to aid students to engage formal physics reasoning in interpreting unfamiliar contexts, thereby potentially enhancing their view of physics as a coherent body of knowledge.

Although research findings on teaching and learning are widely accessible to academics, teachers are as a rule not well informed about appropriate findings (Duit

et al. 2014). While most of the available assessment methods to obtain information on student learning are time consuming, and consequently impractical for teachers to use (Treagust 2012) as mentioned before, the problem of time limitations can be overcome by implementation of Elby paired type questions. By implementing such question pairs, science teachers can achieve better understanding about the nature of students' difficulties in understanding and identify alternative conceptions by using these multiple-choice diagnostic items during tuition of a specific topic (Treagust 2012). Furthermore, the cognitive conflict that arise from students' uncertainty regarding the correctness of their answers of such paired questions allows for students' self-diagnosis of their epistemological views/expected outcomes for comparable situations.

While it is normally easy to identify problems that students experience, it is far more difficult to use such problems as a starting point for finding potential solutions. The major contribution of this study of the impact of change in context of otherwise similar problems is that these data allow for the proposing of a *problem fixing*—as opposed to *problem pointing*—approach to an old but persisting phenomenon. By using alternative conceptions as diagnostic instruments and changing the content of the alternative conceptions into content for instruction, we turned adversity into advantage.

Compliance with Ethical Standards

Disclosure Statement No financial benefits will arise from the direct application of our research.

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CHAPTER 5: ITERATION 2 - ENHANCING CONCEPTUAL COHERENCE

5.1 Introduction

Good teaching encompasses the skilful sequencing and orchestration of tasks and classroom discourse to promote learning, as well as the use of tools that enable each student to conduct and assess their own understanding of subject matter (Edelson, 2002). The research problem described in Chapter 1 as well as the extent of the research problem (described in Chapter 4), pointed to the need for a fine-grained teaching sequence that addresses the various circumstances that influence students' conceptual understanding of introductory mechanics concepts. In this chapter I report on a teaching sequence intended to address some of the core issues identified in the grounding phase of the research. This sequence was implemented as the second iteration of the DBR study. The rationale for this iteration is presented in the next section in terms of the detailed research question that underpinned it, followed by a short description of the aims of each of the different parts of the iteration. After the sampling, methodology, data collection and modes of analysis are described, the results are presented and discussed. The chapter concludes with a reflection on the iteration and a summary of the research and subsequent iterations that were informed by this iteration.

5.2 The design of the teaching sequence

The conclusion reported in Chapter 4 highlighted the persistent nature of the alternative conception that heavier objects fall faster. It seems that the use of conditional statements such as “in the absence of air resistance and/or friction” contributes to the lack of student conceptual understanding of some concepts in the domain of introductory mechanics. The circumstances identified that should receive explicit attention were the presence of conditional statements such as “in the absence of air resistance and/or friction” in questions on non-horizontal motion, the influence of context on student conceptual understanding and the modelling of physical phenomena through the use of multiple representations. The detailed research question that underpinned this iteration was: To what extent does i) explanation of conditional statements and ii) the use of multiple representations of motion in different contexts contribute to student understanding of i) the concept of net force and the acceleration associated with net force, and ii) the conceptual relationships between the physics variables. The purpose of this iteration was to develop a teaching sequence that could enhance the quality of students' conceptual understanding of Newton's second law; in particular, the conceptual relationship between net force, mass and acceleration, paying special attention to the above mentioned circumstances.

The teaching sequence aimed to:

- enhance student conceptual understanding of one of the core concepts in introductory mechanics, namely net force, by clarifying the use of conditional statements such as “in the absence of air resistance and/or friction”
- implement a series of representations that focuses on enhancing student conceptual understanding of net force in a variety of linear motion contexts (horizontal motion, motion on an inclined plane and vertical motion)
- develop qualitative mathematical reasoning.

The detailed research questions formulated to guide the evaluation of the teaching sequence were:

To what extent does a) explanation of conditional statements and b) the use of multiple representations of motion in different contexts contribute to student understanding of i) the concept of net force and the acceleration associated with net force, and ii) the conceptual relationships between the physics variable for motion under gravity?

The teaching sequence described in this iteration is designed to promote students’ mental construction of relational Newtonian mechanics concepts through implementing the following principles:

- Explicitly addressing the circumstances identified to influence the conceptual understanding of poorly understood mechanics concepts, approaching the learning of the concepts from a refinement instead of replacement perspective (Von Aufschnaiter & Rogge, 2010).
- Extensive use of representations to model the physical system (verbal, written pictorial, diagrammatic, graphical and mathematical)
- Repeated exposure to the coherent Newtonian explanation in different contexts
- Interactive engagement of students who are induced to think constructively about simple Newtonian experiments which produce conflict with their common-sense understandings
- Real world situations and kinaesthetic sensations (which promote student interest and intensity cognitive conflict when students’ direct sensory experience does not conform to their conceptions)

5.3 Design principles of the teaching sequence

In designing the teaching sequence, a beginning point and an ending point were established. The beginning point is referred to as the 'lower anchor', which represents the knowledge students bring with them. The upper anchor represents the expectations one has of student learning at the end of the teaching sequence, that is, what students should then know and be able to do (Duschl *et al.*, 2011). Motion in a horizontal dimension is taken as the lower anchor of the disciplinary concept of net force as prior research results. This is based on the empirical evidence presented in my Master's research, Ferreira (2014), that students answer questions on motion in a horizontal plane with the least difficulty when solving Newtonian mechanic problems. The upper anchor represents the expectation of a more accurate scientific understanding and increasing sophisticated scientific practices.

The approach adopted in this teaching sequence when deciding on the activities to be included in the iteration was that building on student existing conceptions is more likely to foster conceptual change than refuting or attempting to replace existing conceptions (Hewson, 1982; Gunstone, 1987; diSessa & Sherin, 1998; Duschl *et al.*, 2011; Von Aufschnaiter & Rogge, 2015). This view of building on existing conceptions, which is at the heart of design principle 1, p. 50, entails that acceptable scientific conceptions are developed by acknowledging and revising student's alternative conceptions instead of expecting the students to replace their conceptions on the basis of being told to do so (design principle 2, p. 50) (Gunstone, 1987). In accordance to design principle 3 (p. 50) the teaching sequence was designed to present net force from a qualitative perspective. Specific representations to i) enhance understanding of gravity as the net force for free falling objects and ii) introduce qualitative reasoning to advance conceptual coherence were implemented (design principle 4, p. 50).

5.4 The teaching sequence: overview and description

The teaching sequence consists of four parts, each with a specific focus spread over two three-hour contact sessions offered on alternative Saturdays (see Figure 5-1 for a schematic representation of the sequence). Part 1 focuses on the extensive use of multiple representations in the context of accelerated horizontal motion (design principle 4). Part 2 consisted of a practical experiment concerning the effect of constant force and acceleration in the context of horizontal motion. A discussion on alternative conceptions was incorporated in Part 2 (design principle 2). Part 3A, was similar to the experiment done in Part 2, but with the motion taking place along an inclined plane, while vertical downward motion formed the focus in Part 3B. My previous research has indicated that students were less confused with the net force-mass-acceleration relationship for motion on a horizontal plane than for non-horizontal motion (Ferreira, 2014). Therefore, for

Part 3, A and B, the focus was specifically on the implication of the conditional statement: in the absence of air resistance and/or friction. The presence or absence of the alternative conception that heavier objects fall faster after instruction has therefore been used as a measure of the extent to which the intervention was successful. The focus of Part 4 was the particular sequence in which all the elements were incorporated: the employment of multiple representations, with their associated affordances, a focus on conditional statements and the introduction of qualitative proportional reasoning (design principle 4).

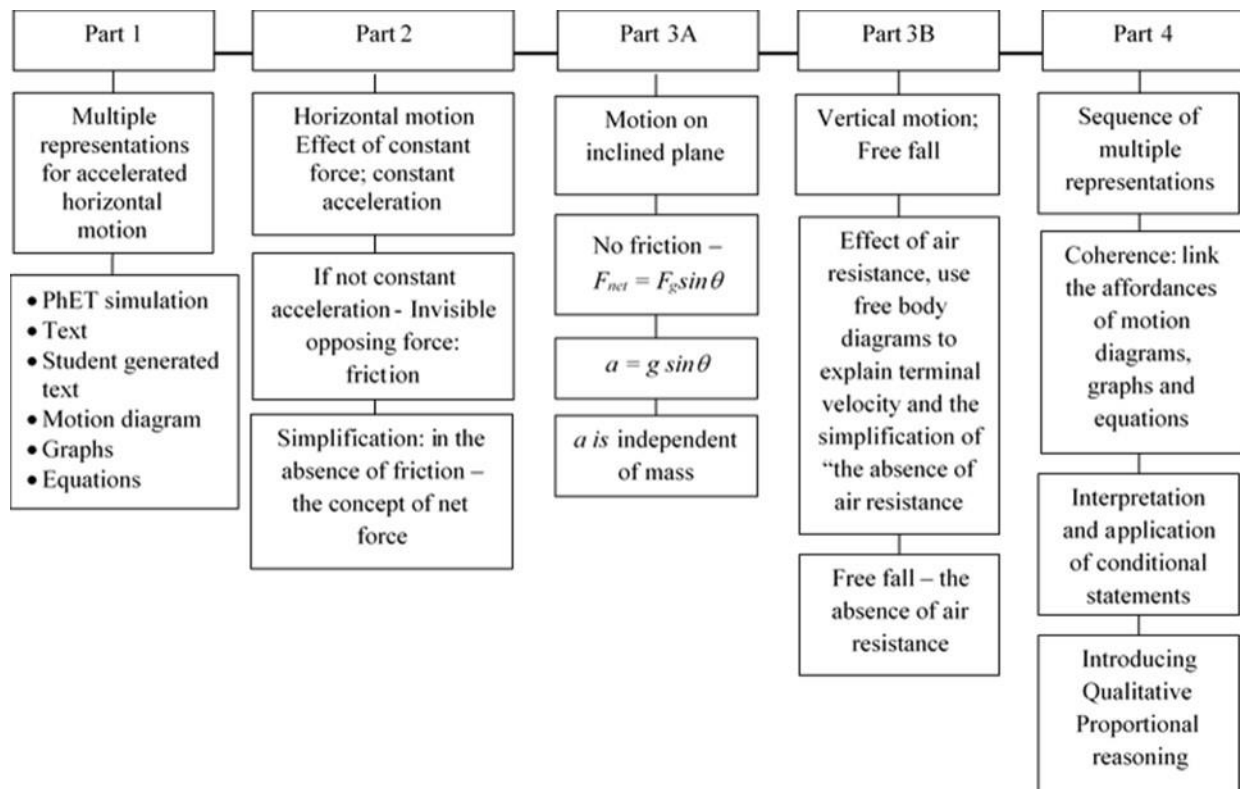


Figure 5-1: Diagrammatic representation of the parts of the teaching sequence

5.4.1 Part 1: The use of multiple representations

Part 1 entailed the use of a computer simulation program for motion along a horizontal plane combined with worksheets to be completed by the students. It was conducted in a three-hour session. The purpose of Part 1 of the sequence was twofold: i) to investigate student understanding of acceleration as the traditional time-dependent change in velocity approach and, ii) to illustrate the coherence of physics concepts by combining the affordances of multiple representations.

Pre-instruction questionnaires:

To establish the current level of the participants' ability to link physics concepts with the relevant mathematical representations, two pre-instruction questionnaires were administered to all the

students at the start of the session (See Appendix B). The first questionnaire was compiled specifically for this iteration and consisted of questions where students had to i) link the variables represented on the axis to the shape of the graph and /or ii) relate the slope of the graph to an equation that would be a mathematical representation of the graph. The questions were formulated to identify possible gaps in student knowledge of the relationship between physical and mathematical representations of kinematic relationships, for example, the shape of kinematic graphs and the variable on the x-axis of each graph, and the mathematical representation of the relationship represented by the graph.

After completion, the first pre-instruction questionnaire was discussed with the students to clarify the information offered by different aspects of graphs. The participants' responses to the first pre-instruction questionnaire test confirmed that the activities I planned regarding the content and progression of the teaching sequence were appropriate. A second pre-instruction questionnaire was also completed to allow comparison of student pre-post-instruction responses. The second pre-instruction questionnaire is presented as Appendix D.

Activity 1: Verbal and pictorial representations

Preparation: The PhET simulation "The Moving Man" developed by the University of Colorado Boulder (n.d.) (<https://phet.colorado.edu/en/simulations/category/physics>, University of Colorado Boulder, n.d.) was uploaded on the server in a computer laboratory, thus allowing the students to complete the worksheets for this part by running the simulation on individual computers.

The simulation was run, providing the students with a text and pictorial representation of how a change in one or all four variables (displacement, direction of motion [by choosing the direction of velocity and acceleration], velocity, acceleration) influences the motion of a man. Each participant was required to provide a description of the resultant movement as each variable was changed. For example, moving the position dial 1 m to the right of the equilibrium or start position changed the position variable. The velocity, as well as the acceleration was kept on zero. The participant was then expected to provide a description similar to the statement 'Man stands 2 m to the right of the origin and remains stationary' (see Figure 5-2 and Table 5-1).



Figure 5-2: Example of pictorial representation of the PhET –simulation “The Moving Man”

The purpose of this exercise was to illuminate the relationships between the different kinematic variables (displacement, velocity and acceleration) as well as the vector nature of the variables. The animation enabled the students to observe that negative acceleration does not always mean slowing down and that positive acceleration does not always mean speeding up. In fact, this allowed me to explain that the label of a “positive or negative” variable should be interpreted in terms of the frame of reference and not in terms of the direction of motion. This was helpful for the next activity in which the link between the verbal representation and a motion diagram to ‘visualize’ the motion was made with the intention to relate them to the various graphical representations of the same motion.

Activity 2: Adding Physical-mathematical representations (motion diagrams and kinematic graphs)

Activity 2 linked verbal representations generated by the students to motion diagrams and an accompanying set of kinematic graphs that represents the original motion represented in the PhET simulation. The purpose of this activity was to emphasize the coherence between various representations and their affordances. Motion diagrams were incorporated to represent the real movement depicted in the pictorial representation i.e. to visualize the animated motion. Figure 5-3 is an example of how the motion diagrams assisted in drawing and interpreting the shapes of the various kinematic graphs in terms of the related motion. Combining representations in this

way presented an opportunity to explain and understand kinematic graphs conceptually before incorporating any mathematical equations. The contribution of motion diagrams to clarifying and relate a verbal description of motion to graphic representations and equations is illustrated in the section on results (refer to Section 5.5).

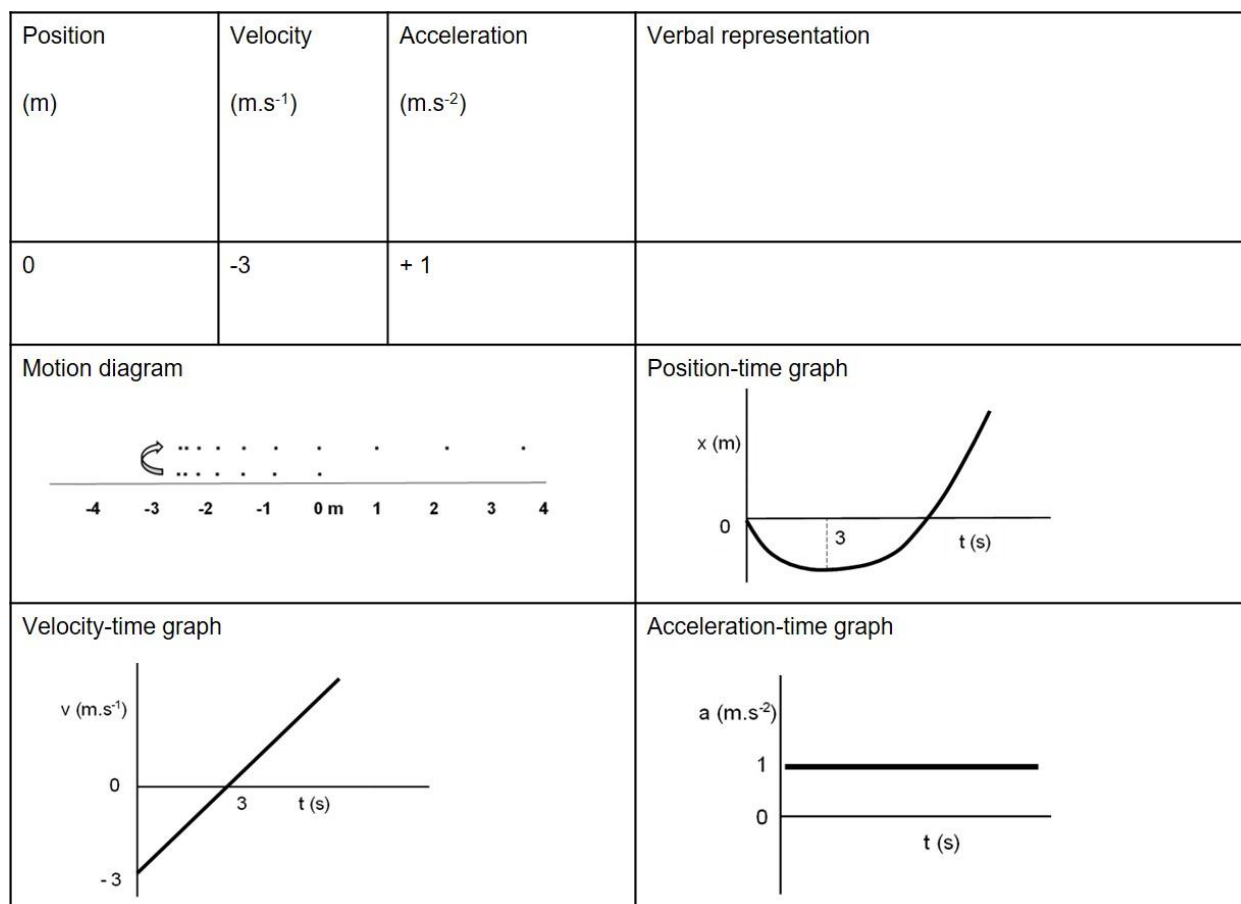
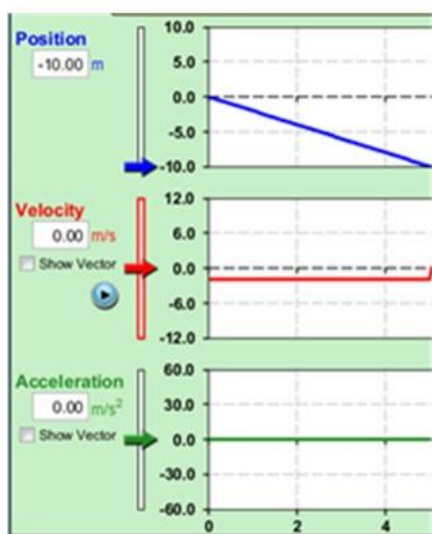


Figure 5-3: An example of linking motion diagrams with the various kinematic graphs

Activity 3: Mathematical equations

This activity was intended to link the graphical representations of the motion to the mathematical representation of the relationships between the variables namely, the equations that describe the motion. Figure 5-4 below is an example of linking different kinematic graphs with the equations that represent the relationship between the physics variables.



(a) Use the s-t graph to verify the v-t graph.

$$v = \frac{\Delta x}{\Delta t}$$

$$v = \frac{-10 - 0}{5 - 0}$$

$$v = -2 \text{ ms}^{-1}$$

(b) Use the v-t graph to determine the position after 10 seconds.

$$\text{position} = \text{displacement}$$

$$x = \text{area under graph}$$

$$x = (-2)(5)$$

$$x = -10 \text{ m}$$

(c) Use the v-t graph to determine the acceleration.
(gradient of graph)

$$s(x) = vt + 0$$

(d) Write the equation of the s-t graph

$$s = -2t$$

$$y = mx + c$$

$$\therefore y = -2x$$

Figure 5-4: Example of linking graphs with appropriate kinematic equations

The representational constellation and sequence used in this part is summarized in Figure 5-5.

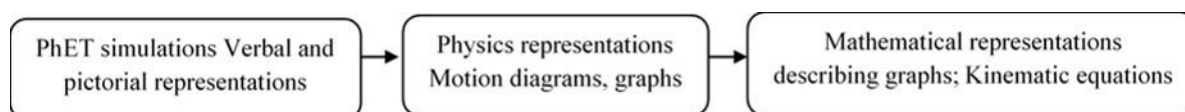


Figure 5-5: A schematic diagram of the sequence in which the multiple representations were implemented in Part 1

5.4.2 Part 2: A practical experiment concerning accelerated motion on a horizontal plane

Part 2 consisted of an experiment in which the effect of a constant force on an object moving on a horizontal plane was investigated. The experiment was conducted during a 3-hour session. The purpose was to reveal the presence (or absence) of the alternative conception that a force is needed to keep an object in constant motion. The activity furthermore served the purpose of raising student awareness of the alternative conceptions of “force as mover” and “a constant force is needed to keep an object moving”. The presence of “unseen” opposing forces was highlighted to emphasize the net-force-mass-acceleration relationship. The broader purpose was to create awareness of alternative conceptions among the members of the instructional group and to enhance the concept of net force for motion along a horizontal plane. In Parts 2 and 3A of the teaching sequence, the experiments followed an adapted form of POE (Predict-Observe-Explain) where the P and O are not of the same event (White & Gunstone, 1992). (See Figure 5-6 below.)

This served as the platform to reveal student alternative conceptions. The choice to not have the P and O of the same event was a pragmatic one due to time constraints. It required less time to have the students make a prediction on an event from memory and then perform a practical experiment that related to that event, than to do the practical activity on a hockey field for example, and repeat it in circumstances where less friction is encountered than on a hockey field.

Student intuitive knowledge was purposefully recalled by posing a question about a common everyday situation. This was done to enhance the expected cognitive conflict created by the difference between their predictions and observations in the practical activity that followed. This activity required the students to predict and then act out the effect of applying a constant force on an object moving from rest on a smooth horizontal plane. Following the activity, the students had to compare their predictions and observations and interpret the differences or similarities in terms of physics concepts. By using this protocol, student alternative conceptions that influenced their ability to apply physics concepts to everyday situations correctly were revealed. The conditional statement “in the absence of friction” was interpreted to enhance student understanding of the concept of net force. Figure 5-6 presents the scenario on which the POE protocol was based.

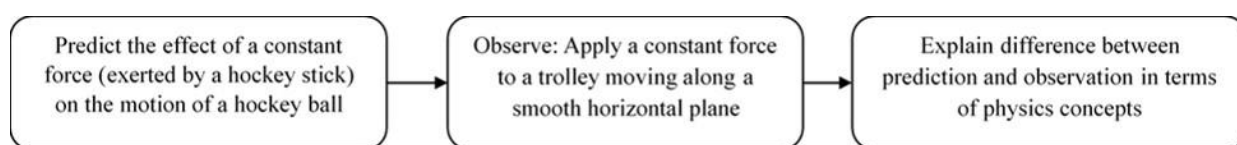


Figure 5-6: Progression of the POE protocol followed in Part 2

The teaching sequence followed the outline described below:

5.4.2.1 Predict: The effect of a constant force on the motion of an object

A self-assessment question on an everyday situation served to probe understanding of the effect of a constant force on an object: a hockey player exerts a constant force on a hockey ball as she dribbles the ball. The question concerned the change in motion of the ball while it is being dribbled and kept in contact with the stick.

5.4.2.2 Observe: Experiencing the effect of a constant force on a horizontally moving object

The prediction part was followed up with a simple experiment in which the effect of a constant force on an object moving on a horizontal plane was observed.

Investigation:

- (1) Hook a spring scale to a trolley and stretch the scale to a fixed amount so providing a constant force while holding the trolley (Figure 5-7).

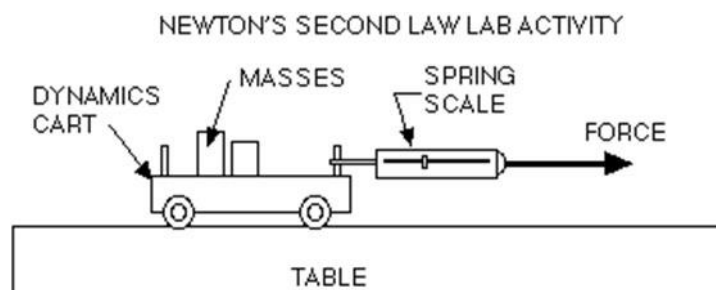


Figure 5-7: Set-up of trolley for experiment

(from <http://www.batesville.k12.in.us/physics/phynet/mechanics/newton2/Labs/Newt2Lab.html>)

- (2) Now release the trolley and move forward with it, keeping the scale stretched the same amount all the time. Try to keep up with the trolley.

5.4.2.3 Explain: Compare the prediction with the observation

The adapted POE protocol followed in this activity was designed to encourage students to become more aware of their alternative conceptions of “force as mover” as well as “constant force is required to ensure constant velocity”.

The concept of friction and the conditions required to minimize the effect thereof were discussed and clarified in this part of Part 2.

This activity presented me with an opportunity to link the multiple representations (e.g. pictorial, force diagrams, motion diagrams) to illustrate the concept of net force and also to relate acceleration to the effect of the net force on an object. The discussion on the use of conditional statements, often encountered in physics, offered a teachable moment to illustrate why and how everyday situations are converted into idealized theoretical physics situations. The use of conditional statements was especially valuable for interpreting the activities that followed in Part 3.

5.4.3 Part 3: Relating acceleration along non-horizontal planes to the component of the force of gravity parallel to the non-horizontal plane

The third part of the teaching sequence served to expand what was learned in part 2 to non-horizontal contexts in order to generalize the concept of acceleration as the effect of a net force.

From the results obtained in Chapter 4, the first iteration of the research, it was clear that many students think physics concepts apply differently to motion in different directions. The purpose for changing the direction of motion from horizontal to inclined plane to vertical motion was to encourage the view of physics as a coherent web of concepts that are applicable in various contexts.

The execution of each of the Parts 3A and 3B was the same as that for Part 2, with the difference that the motion now was along non-horizontal planes, i.e. along an inclined plane (Part 3A), and vertically downward motion (Part 3B). In these two parts the net force to mass ratio was used to address the specific alternative conception that heavier objects move faster under the influence of the force of gravity. Any cognitive conflict between student predictions in the POEs and their observations was addressed during the “Explain” part of the protocol. Part 3B of the sequence took the form of theoretical questions (“thought experiments”), which focused on the concept of free fall. The approach for this section was from a Phenomenon Based Learning (PBL) perspective (Krajcik, 2016); of which more detail is given in Section 5.2.4.2. Acceleration along an inclined plane (Part 3A), and vertical downwards motion (Part 3B) were investigated and discussed with the specific aim to focus on the concept of motion under gravity and draw attention the alternative conception that heavier objects fall faster.

5.4.3.1 Part 3A: A practical experiment concerning acceleration along inclined planes

An experiment following the POE protocol was executed to determine the acceleration of a ball moving down different inclines. The first activity of the experiment was to let the students feel how the force on the object changed with changing incline, using the hand as a crude qualitative sensory force meter. From the second activity onwards a traditional mathematical approach was followed. The worksheets for the experiment are attached as Appendix C.

Activity 1: “Feel the force”: Investigate the relationship between the force and angle of incline experimentally. Figure 5-8 is a schematic representation of the process.

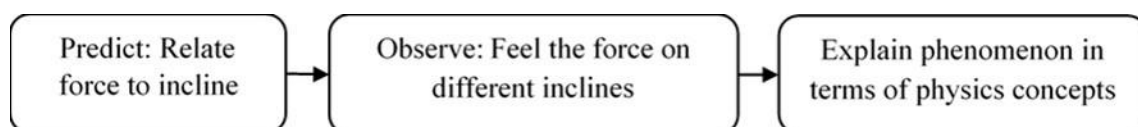


Figure 5-8: Proceedings of Activity 1 of part 3A

The students were asked to keep a hand against the static object and feel how “hard” the object pressed against the hand as a measure of the force acting in a vertical direction. Initially the object was on a horizontal plane; therefore, they felt “no force”. As the incline increased the object pressed harder against the hand, indicating that the vertical force on the object increased. When

the incline was at a 90° angle the force against the hand was the biggest. The next activity was intended to link the force on different inclines to the acceleration on different inclines by means of the mathematical relationship between the component of the gravitational force and acceleration.

Activity 2: Determine how the angle of an inclined plane effects the acceleration of a trolley down the inclined plane.

The objectives of this activity were twofold: i) to relate the net force experienced by an object on a frictionless inclined plane to the component of the gravitational force and ii) to deduce a generic equation to show that all objects would experience the same acceleration on the same incline, regardless of their mass. The different physics representations used in this activity were chosen according to their affordances to reinforce and relate physics concepts. For example, drawing force diagrams to emphasize the concept of net force, and deducing a generic equation to represent the relationship between the angle of incline, the net force and acceleration, assisted in explaining that the acceleration of similar objects with different masses along a smooth inclined plane was independent of the mass.

In Activity 2 the students determined the acceleration of a trolley along an inclined plane with varying inclines. First they calculated the theoretical net force and the acceleration of the object along the plane at three different angles, then they performed an experiment in which the times for travelling down the length of the plane were measured for the same angles as those for which the theoretical values were calculated. The acceleration and the related net force were calculated from the measurements for the three different inclines. After calculating the net force in terms of the component of gravitational force parallel to the inclined plane, the two values (experimental and calculated) of the net force were compared and the discussion on the effect and minimisation of friction was repeated. A generic equation for determining the acceleration of an object along a frictionless inclined plane was deduced. Figure 5-9 is a schematic presentation of the proceedings of Activity 2.

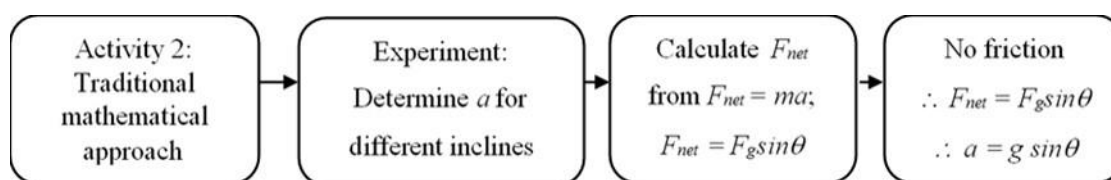


Figure 5-9: Schematic representation of proceedings of Activity 2 of part 3A

5.4.3.2 Part 3B: Acceleration of object in free fall

Part 3B, a qualitative experiment that included a demonstration around vertical downward motion, was conducted during one 3-hour session. The aim of the activities in part 3B was to extend the

conclusions from part 3A to vertical motion. The section on vertical motion was introduced by hypothetical questions on the underlying principle of gravitational acceleration and free fall, and followed a Phenomenon Based Learning (PBL) approach. Figure 5-10 is a visual presentation of the approach reproduced from Krajcik (2016).

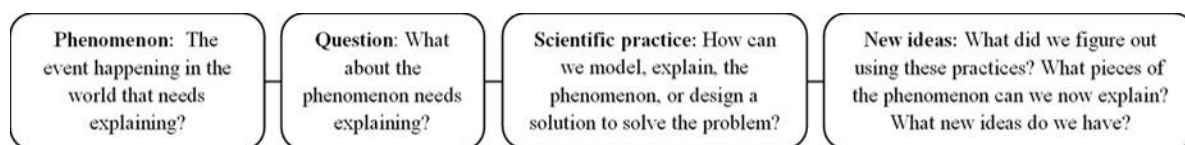


Figure 5-10: Representation of the Phenomenon Based Learning approach

The POE protocol was followed once again for two demonstrations, one involving a steel ball and a polystyrene ball of the same size but different mass, and the other involving a set of paper cups designed for cup-cake making with one single cup and two cups pushed into one another to form a unit. The mass of the steel ball was more than 250 times the mass of the polystyrene ball where the mass of the double cup was twice that of the single cup. The set of balls and the set of paper cups were respectively released from the same low height of about 50 cm as two separate demonstrations. The two balls appeared to hit the ground at the same time but the double paper cup fell observably faster than the single cup and clearly hit the ground first. The purpose of the demonstration was to show that heavier objects do not always fall faster. The cognitive dissonance created by the demonstration served as an introduction to investigate and explain the factors that determine whether air resistance would have an observable effect on the motion of objects or not, and what ignoring the effect of air resistance would mean in terms of the physics variables associated with motion. Figure 5-11 is a schematic representation of Part 3b.

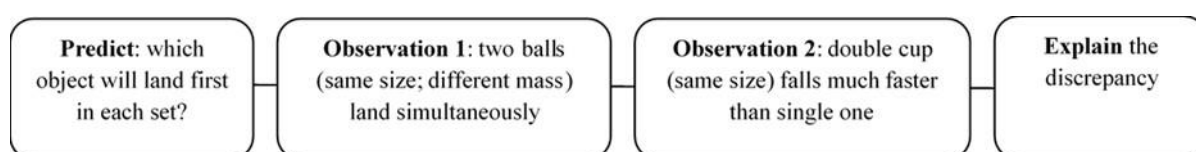


Figure 5-11: Schematic representation of POE protocol for part 3B

I explained the apparent discrepancy in the observations in terms of the air resistance experienced by falling objects. The equation for air resistance, combined with force diagrams, was used to explain the concept of terminal velocity and to highlight the significance of the height from which objects fall for observation of the effect of the phenomenon of air resistance. Figure 5-12 shows how the PBL approach was applied to the phenomenon.

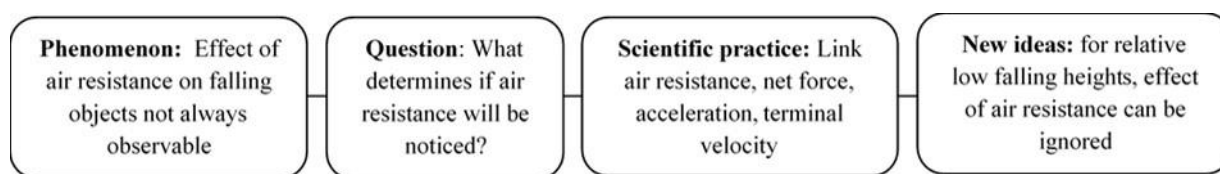


Figure 5-12: PBL approach for part 3B

The notes containing the diagrams and explanation used in Part 3B are included in Appendix C. The expected result was that student perception of physics as a set of coherent concepts would be enhanced by explaining the consequence of simplifying the relevant problem through conditional statements that expose the underlying physics principles. In the next two iterations of the DBR, described in chapters 6 and 7, more detail about the effect of explaining conditional statements on student understanding of motion under gravity is given.

5.4.4 Part 4: Bringing it all together

In the final part (Part 4) of the sequence the students were introduced to qualitative conceptual reasoning, using multiple representations, which included equations without any numeric values for the variables. For example, acceleration was considered from an alternative conceptual approach as the net force to mass ratio, in addition to the traditional mathematical time derivative of velocity approach. My approach towards this part is set out in Appendix E.

In Part 4 the outcomes of the preceding three parts were summarized and combined to be used as introduction for qualitative, conceptual problem solving. After reaching consensus on the validity and consequence of conditional statements such as “in the absence of air resistance and friction”, various kinematics questions in which the motions of two objects were compared qualitatively were discussed. By relating the affordances of different representations of a question, as described below in this paragraph, the students were shown that knowledge could be transferred between representations, and how different representations enhanced coherence of the various concepts in kinematics. The representations used for the problems discussed in Part 4 were i) verbal (text), ii) pictorial, iii) motion diagrams and iv) equations. For example, a problem in which the motion of two related objects has to be compared qualitatively was first presented verbally (in text). After the students drew a picture to visualize the problem, they had to construct a motion diagram for each object to show the relative motion. The motion diagrams were then used to compare and relate different kinematic variables qualitatively. Finally, this qualitative information was used in applying the appropriate physics equation/s as reasoning tool to solve the problem. The worksheets attached in Appendix C provide examples of how the different representations were applied. The questions reported on in this iteration is presented in Table 5- 2 in Section 5.6.1.1. Figure 5-13 is a schematic representation of the process.

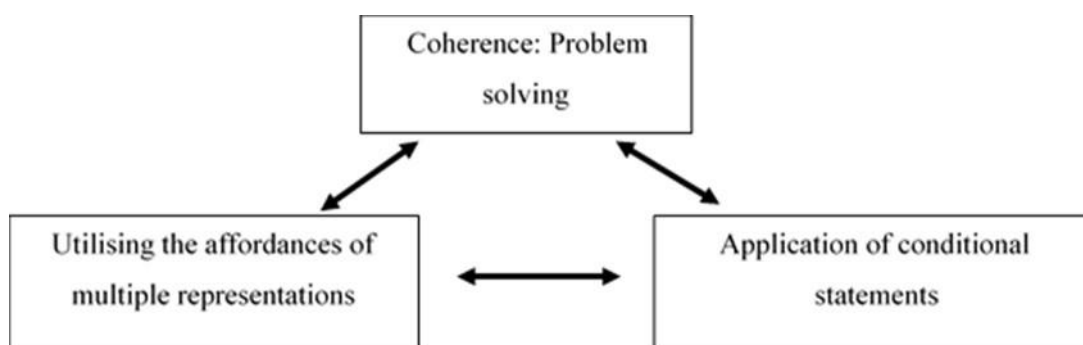


Figure 5-13: Schematic representation of the affordance of relating different representations

5.5 Implementation of the teaching sequence

5.5.1 Participants

The research group consisted of a convenient population of eight in-service teachers ($n=8$) enrolled for a B.Ed. Honours in Science Education course, a postgraduate degree for practising teachers. Three of the participants had B.Sc. degrees, while the other participants had B.Ed. degrees. None of the participants had Physics beyond a first year introductory level in their undergraduate studies. Their disciplinary content knowledge could be taken to be at an introductory level. Some of the participants had between three and five years' teaching experience while others were novice teachers with less than three years' teaching experience.

5.5.2 Data collection

The instruction formed part of the mechanics topic for the B.Ed. Honours curriculum. All the participants completed the diagnostic as well as the pre-instruction questionnaires during the first session. Three participants attended all the sessions while the others attended the sessions intermittently. As a result, the number of respondents for the other forms of qualitative data collection varied depending on the number of students who attended a particular session.

5.5.3 Research instruments

Data were collected by administering pre- and post-instruction questionnaires to the participants. An adapted version of the questionnaire used in the first iteration (see Chapter 4), was given as a pre-instruction questionnaire for Part 3 (see Appendix D). The questionnaire was administered for two reasons: firstly, to determine whether the in-service teachers experienced the same difficulties regarding alternative conceptions and the direction of motion as had been revealed in iteration 1 (refer to Chapter 4), and secondly, to establish a baseline of the participants'

conceptual understanding for comparison with their post-instruction answers. The questionnaires were administered in a natural classroom setting as part of the normal course schedule of the students.

The participants were required to complete worksheets (taken from Lemmer (2011)) that accompanied the teaching sequence at the end of Part 4 (see Appendix F). These worksheets were also analysed to establish the extent to which the teaching sequence succeeded in addressing the research questions. Some questions of the pre-instruction questionnaire were repeated in the worksheets while other questions were variations of the questions used in the pre-instruction questionnaire.

5.5.4 Data analysis

Due to the small population for whom complete data sets were possible, the data were only analysed qualitatively. The pre-and post-instruction data served to identify common difficulties that needed to be addressed. A frequency table of student responses to the pre-questionnaire of Part 3 was compiled to show the trend in student responses. Content analysis of the pre- and post-instruction results (worksheets) of students were done to compare individual students' pre- and post-instruction answers. This was done to determine whether the instruction focussed on alternative conceptions and simplification was incorporated in student post-instructions answers and to compare the student use of multiple representations pre- and post-instruction.

5.6 Results

5.6.1 Pre- instruction questionnaire results and discussion

This section reports on the collective student responses to questions in the pre-instruction questionnaire (Appendix D) from Part 3 that were repeated in the worksheets that the students completed after Part 4 of the iteration. The responses were divided into two subsections; the first subsection (5.6.1.1.) contains the responses to questions 2, 5 and 7 while the second subsection (5.6.1.2) reports and discusses responses to question 3.

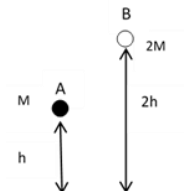
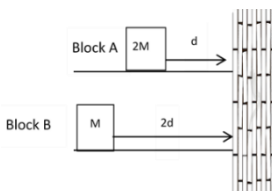
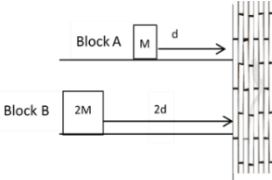
5.6.1.1 Student responses to questions 2, 5 and 7

Questions 2, 5 and 7 all described the same situation: two objects of the same mass were released or moved simultaneously with identical accelerations over different displacements, towards a certain destination. One object was to travel twice the displacement of the other one. Question 2 was set in vertical downward motion while questions 5 and 7 were set in horizontal motion. Each answer required a prediction as to which object would reach the destination first (i.e. moves for a shorter time). In question 2 identical gravitational acceleration for the vertical

downwards motion had to be inferred, in question 5 equal acceleration was stated, while in question 7 it was expected that the students would infer equal acceleration from the force to mass ratio.

In total, for all three questions combined the correct option was chosen in only 11 of the possible 24 times, while the incorrect answer appearing the most ($N=9$) was that the objects would reach their destination simultaneously (S). Some students answered two of the three questions correctly but not the third and only one student had all three correct. Table 5-1 presents the options to questions 2, 5 and 7.

Table 5-1: Responses 2, 5 and 7 of questionnaire

Context	Question	Options
↓t infer $a=g$	2. Two metal balls are dropped simultaneously from different heights. Ball A has half the mass of ball B but falls half the displacement to the ground. Ignore the effect of air resistance.  Which ball will reach the ground first?	Ball A. Ball B. Both will reach the ground simultaneously
→t given $a=\text{equal}$	5. Two blocks with different mass are simultaneously pulled from rest along a horizontal plane with identical constant accelerations. Block A has twice the mass of B but has half the displacement of block B.  Which one will reach the wall first? Friction must be neglected	Block A. Block B. Both will reach the wall simultaneously because B has a bigger displacement and reaches a larger speed.
→t infer $a=\text{equal}$	7. Two blocks, A (mass M) and B (mass $2M$), are simultaneously accelerated from rest over different displacements. The force on block B is twice the force on block A and the displacement over which B is accelerated is twice that of block A. Friction must be neglected  Which block will reach the wall first?	Block B because it reaches a larger speed. Both will reach the wall simultaneously because B has a bigger displacement and reaches a larger speed. Block A because it has a shorter displacement.

The correct answer for all the questions was that object A (travelling the shorter displacement) would reach its destination first. In all three situations the effect of opposing forces was to be ignored, hence I expected the common-sense response that the object closest to the destination (A) would reach it first. The student answers to the respective questions are presented in Table 5-2. In the table “A” indicates that A was chosen to arrive first; “B” indicates that B was chosen to arrive first and ‘S’ indicates the choice that the objects would arrive simultaneously.

Table 5-2: Pre-instruction answers to questions 2, 5 and 7

	Student 1	Student 2	Student 3	Student 4	Student 5	Student 6	Student 7	Student 8	Correct
Q2	S	A	A	A	S	A	S	A	5/8
Q5	S	S	A	A	A	S	B	B	3/8
Q7	A	A	A	S	B	S	S	B	3/8

Discussion of results

The difference in responses to questions 2 and 7 points to a lack of conceptual understanding of acceleration as the net force to mass ratio. While in question 2 equal gravitational acceleration was implied, the students had to infer equal acceleration in question 7 from the force to mass ratio. The choice of the “simultaneous” option in question 2 indicated the possible presence of the alternative “heavier objects fall faster” conception, while choice of the “simultaneous” option for question 7 may indicate the incorrect conception that a bigger force produces a bigger acceleration, regardless of the proportionality between the forces and the respective masses.

Student failure to relate equal acceleration in terms of the displacement travelled in the questions above points to a difficulty to translate their interpretation of the problem to an equation that shows the relationship between the relevant physics quantities. These results indicate inconsistencies in student reasoning to relate respective applicable physics variables and use proportional relationships.

As reported in Chapters 2 and 4 the direction of motion appeared to influence student responses to comparable problems. Interestingly though, in this iteration more students answered questions on horizontal motion wrong than questions on vertical motion. Due to the small sample no inference can be made from this observation. However, future investigation may prove useful regarding student perception of implementing Newton’s second law in vertical versus horizontal motion.

5.6.1.2 Student responses to question 3

This question, presented in Table 5-3, concerned a heavily loaded truck and a motorcar initially travelling side by side on a highway and coming to a halt at the same time at the same place. The mass of the truck is double that of the car. Because the question concerned the *magnitude* of the two forces, the forces are not indicated as vectors in the table below.

Table 5-3: Question 3 of questionnaire

Question number	Question	Options
Q 3	A heavily loaded truck, and a motorcar travel side by side on a highway. The mass of the truck is double that of the car. The drivers notice the changing traffic light and start to apply the brakes at the same time and come to a halt at the traffic light simultaneously. Neglect the effect of friction. Which statement below is true for the magnitude of the force applied by the brakes? acceleration experienced by the vehicles?	$F_{\text{truck}} = 2 F_{\text{motorcar}}$ $F_{\text{truck}} = \frac{1}{2} F_{\text{motorcar}}$ $F_{\text{truck}} = F_{\text{motorcar}}$ $a_{\text{truck}} = 2 a_{\text{motorcar}}$ $a_{\text{truck}} = \frac{1}{2} a_{\text{motorcar}}$ $a_{\text{truck}} = a_{\text{motorcar}}$

The expectation was that the students should be able to deduce the correct answer qualitatively. The initial and/or final velocity had to be related to the displacement or time and the force-mass-acceleration relationship of the moving objects had to be considered. The correct answer for the ratio of the forces experienced by the objects was $F_{\text{truck}} = 2 F_{\text{motorcar}}$ whereas the acceleration of the objects was equal. The individual student answers are presented in Table 5-4.

Table 5-4: Student responses to question 3

Correct answer:	Q3 (F) $F_{\text{truck}} = 2 F_{\text{motorcar}}$	Q3 (a) $a_{\text{truck}} = a_{\text{motorcar}}$
Student 1	$F_{\text{truck}} = F_{\text{motorcar}}$	$a_{\text{truck}} = 2 a_{\text{motorcar}}$
Student 2	$F_{\text{truck}} = \frac{1}{2} F_{\text{motorcar}}$	$a_{\text{truck}} = \frac{1}{2} a_{\text{motorcar}}$
Student 3	$F_{\text{truck}} = 2 F_{\text{motorcar}}$	$a_{\text{truck}} = a_{\text{motorcar}}$
Student 4	$F_{\text{truck}} = 2 F_{\text{motorcar}}$	$a_{\text{truck}} = a_{\text{motorcar}}$
Student 5	$F_{\text{truck}} = 2 F_{\text{motorcar}}$	$a_{\text{truck}} = 2 a_{\text{motorcar}}$
Student 6	$F_{\text{truck}} = \frac{1}{2} F_{\text{motorcar}}$	$a_{\text{truck}} = \frac{1}{2} a_{\text{motorcar}}$
Student 7	$F_{\text{truck}} = \frac{1}{2} F_{\text{motorcar}}$	$a_{\text{truck}} = 2 a_{\text{motorcar}}$
Student 8	$F_{\text{truck}} = \frac{1}{2} F_{\text{motorcar}}$	$a_{\text{truck}} = \frac{1}{2} a_{\text{motorcar}}$

Two students (3 and 4) chose the correct options for the force and the acceleration, four students gave the inverse of the correct proportionality for the force (i.e. used $\frac{1}{2}$ instead of 2 for the ratio of forces) and five student responses regarding the force and acceleration suggested inconsistent reasoning. One student (student 8) made an incorrect choice for the force but the answer for acceleration was consistent with that (incorrect) force- mass-acceleration relationship.

Discussion

The results suggested an overall difficulty to express verbal reasoning in terms of an appropriate proportional symbolic representation. This was further investigated through qualitatively comparing some pre-instruction responses with post-instruction explanations; this is discussed in more detail below in Section 5.6.2.

5.6.2 Comparison of pre-and post-instruction responses to questions 2 and 3

Questions 2 and 3 were respectively compared in terms of the students' pre- and post-instruction responses, to get an indication of whether explaining the conditional statements and the use of multiple representations had any influence on the students' post-instruction answers.

5.6.2.1 Question 2

Two balls A and B with different mass are at the same time dropped from different heights. The mass of ball A is twice that of ball B. Ignore the effect of air resistance.

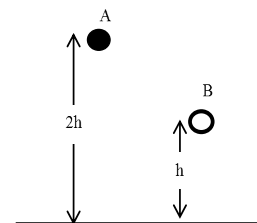
Which ball will reach the ground first?

Ball A.

Ball B.

Both will reach the ground simultaneously.

Please explain your answer as you would to learners



For the post-instruction questionnaire, question 2 (Appendix F) was altered in terms of the height of the two objects. The positions of the balls were reversed in the post-instruction worksheet, therefore ball A was released from the higher height and ball B was closer to the ground and hit the ground first. Examples of responses are given later in this section. For the sake of brevity, the student post-instruction verbal explanations were transcribed and presented as mathematical relations or equations; however, the terms “verbal representation” and “mathematical representation” used in Table 5-6 indicate whether the student gave a verbal or mathematical answer. The summary of the explanations given for question 2 is presented in Table 5-5.

Table 5-5: Summary of student answers to question 2

	Pre	Post- instruction (A the higher ball)
Student 1	S	Verbal representation - S $m_A = 2 m_B$; $F_{gA} > F_{gB}$ therefore $v_A > v_B$ and they will reach the ground simultaneously
Student 2	correct	Verbal representation - S $a_A = a_B$ but because $m_A = 2 m_B$, it means $F_{gA} = 2 F_{gB}$. $h_B = \frac{1}{2} h_A$ and $F_{gA} = 2 F_{gB}$, therefore they reach the ground at the same time.
Student 3	correct	Mathematical representation – B correct $a_A = a_B = g$ Equation: $y = ut + \frac{1}{2}at^2$; substitute relative heights, solve for time. Prove $t_A > t_B$, B will land first because of lower height to cover
Student 4	correct	Verbal representation – B correct When no air resistance B will land first $a_A = a_B$, B moves over shorter displacement, will land when A is still at height h.

Student 3 and 4 gave the correct answers in both pre- and post-tests and their explanations were also correct. In their explanations both students 1 and 2 correlated the bigger force experienced by ball A to its mass.

Discussion of pre-post answers to question 2

Only Student 3 used equations or parts thereof to enhance his verbal explanation. Student 1's statement that the heavier object would "catch-up with the lighter one and hit the ground at the same time" indicated the presence of the alternative conception of "the heavy object falls faster" as well as the incorrect conception that force is related to velocity. Student 2's correct pre-instruction answer and correct post-instruction use of the force to mass ratio, indicate some understanding of the relationships represented by equations as well as using equations as reasoning tools. The incorrect linkage of force, acceleration and displacement (height) indicates that more time is required for students to consolidate their new understanding of using equations as reasoning tools.

The students' inability to either infer the obvious answer that the object covering the shortest displacement would reach the destination first or to translate the information into an equation relating the physics variables with one another, confirmed that they find it hard to transfer between

verbal and equation representations. These results point towards inconsistencies in student reasoning to relate respective applicable physics variables and use proportional relationships.

5.6.2.2 Question 3

A summary of student pre-post answers to question 3 is given in Table 5-6.

Table 5-6: Summary of student pre - and post answers to question 3

	Pre-	Post- instruction
Student 1	$F_t = F_{mca}r$; $a_t = 2a_{mcar}$	$a_{truck} = a_{motorcar}$ $F_{truck} = \frac{1}{2} F_{motorcar}$. Truck will apply more force to stop unlike the car since it is less weight so it would take much force to stop so the $F_{truck} = \frac{1}{2} F_{car}$. In terms of acceleration it will have the same acceleration since they travel at the same velocity, their acceleration will be the same.
Student 2	$F_t = \frac{1}{2} F_{mcar}$ $a_t = \frac{1}{2} a_{mcar}$	$a_{truck} = a_{motorcar}$, $F_{truck} = \frac{1}{2} F_{motorcar}$. Since both drivers applied the brakes at the same time it means that both experience the same acceleration to come to a halt at the traffic light simultaneously. But since the truck's mass is double that of the car the force on the motor car is half compared to the force on the truck.
Student 3	$F_t = 2F_{mcar}$ $a_t = a_{mcar}$	$a_{truck} = a_{motorcar}$ $F_{truck} = 2F_{motorcar}$ $a_{truck} = a_{motorcar}$ (1) – same initial velocity, cover equal displacement at equal times $x = ut + \frac{1}{2} ut^2$ $F_{truck} = m_{truck} a_{truck}$ (2) $F_{motorcar} = m_{motorcar} a_{motorcar}$ (3) But $m_{truck} = 2 m_{motorcar}$ and $a_{truck} = a_{motorcar}$ (1) (2) + (3) $\Rightarrow F_{truck} = 2 m_{motorcar} a_{motorcar}$ $\therefore F_{truck} = 2 F_{motorcar}$
Student 4	$F_t = 2F_{mcar}$ $a_t = a_{mcar}$	$a_{truck} = a_{motorcar}$ $F_{truck} = 2F_{motorcar}$ When two vehicles travel with the same velocity and stop at the same time point simultaneously then their acceleration is the same. $F_{truck} = 2 m_{car} a$ $F_{car} = m_{car} a$ $a_t = \frac{F_t}{2ma}$ and $a_c = \frac{F_c}{m}$ but $a_{truck} = a_{motorcar}$ $\therefore \frac{F_t}{2m} = \frac{F_c}{m}$ $F_t = 2F_c$
Student 8	$F_t = \frac{1}{2} F_{mcar}$ $a_t = \frac{1}{2} a_{mcar}$	$a_t = \frac{1}{2} a_{mcar}$ $F_t = \frac{1}{2} F_{mcar}$ The acceleration of car is half that of the truck since it has less mass. Since $a \propto F$ then it simply means it will be equal to that of the truck. Since motorcar has less mass will require less force to be applied to it.

Discussion of pre-post answers to question 3

The responses of students 3 and 4 in both the pre- and post-instruction tests were correct. Their answers in the post-instruction test showed successful transfer between their verbal representations and equations. The responses of students 1 and 2 pointed to a difficulty to transfer their verbal interpretations (which were correct) to a mathematical relationship. For example, student 2 correctly stated that “the force on the motor car is half compared to the force on the truck”, but chose “ $F_{truck} = \frac{1}{2} F_{motorcar}$ ” to represent the relationship. Likewise, student 1 said: “Truck will apply more force to stop unlike the car ... so the force on the truck is half the force on the car”. Student 8’s response showed that prior knowledge of Newton’s second law is required to be able to interpret the information in any way.

It seems that while using multiple representations can enhance student conception of the coherence of the various representations, students’ poorly developed skills to translate verbal representations into the correct mathematical proportionality are illuminated. The results from these comparisons suggest that qualitative reasoning using equations as reasoning tools can be helpful in conceptually linking physics knowledge to mathematical representations. The results presented in the following section support this notion.

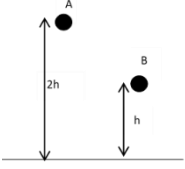
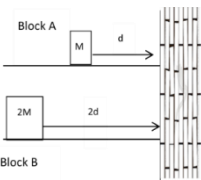
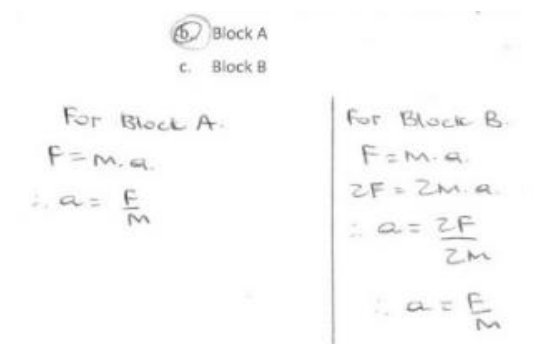
5.6.3 Comparison of isomorphic questions after instruction

Here I report on student responses on two sets of post-instruction isomorphic questions, as presented in Table 5-8. In Set A (Section 5.6.3.1 below) individual student responses on two isomorphic questions set in different directions are compared, while individual student pre- and post-instruction uses of multiple representations are compared in Set B.

5.6.3.1 Responses to Set A questions

The questions in Set A concerned two objects released at the same time and moving at equal accelerations but over different displacements. Question 5 was set in vertical direction while question 6 was set in horizontal direction. The purpose for including these questions was to obtain information on i) the influence of the direction of motion on student understanding of the relationship between the physics concepts, ii) in particular on application of the force to mass ratio to objects of heavier mass in horizontal direction, and iii) the effect of the teaching and discussion done in Part 4 of the instructional sequence. The questions as well as the individual responses are presented in Table 5-7.

Table 5-7: Student post-instruction responses to question 5 (horizontal motion) and question 6 (vertical motion)

	Question 5	Question 6
	 Two balls A and B with the same mass are dropped from different heights and at different times. The initial height of ball A is twice that of ball B. Ball A is released first. Ball B is released at the exact moment that ball A passes ball B at height h. Ignore the effect of air resistance. Which ball will reach the ground first?	 Two blocks, A (mass M) and B (mass $2M$), are accelerated over different displacements. The force on block B is twice the force on block A and the displacement over which B is accelerated is twice that of block A. Block B is moved first. Block A is moved at the exact moment that block B passes block A at displacement d. Friction must be neglected Which block will reach the wall first?
Student 1	Ball A, as it reached the exact moment of (release of ball B) ball A already has a value. Ball B, at the exact moment of release the velocity is zero. So since ball A has an initial velocity it will reach the ground first	They will reach simultaneously, since B started first it has a velocity when it reaches A and A will have zero velocity.
Student 2	Both will reach the ground simultaneously because at that time B is released both A and B are at the same height. Again since both balls have the same mass they will experience the same force to cover the same displacement.	Block B, at that moment block A is released both block A and B have to cover the same displacement, but the force on B is twice that on block A. Since they have to cover the same displacement and B experiencing the greater force, B will reach the wall first.
Student 6	Simultaneously, initially before Ball A is released its initial speed was 0 m/s. When it gets to the same height as ball B, ball B will also be released when its initial speed is 0m/s. They will therefore accelerate downwards at the same rate and reach the ground simultaneously. And with their equal masses, they will both experience equal gravitational force.	 Block A. Now regardless of their masses and displacements, we've proved that both the blocks will accelerate at an equal rate therefore the one that is upfront will reach the wall first

Discussion of pre-post answers to questions 5 and 6

Student 1 interpreted the information correctly in the vertical but not in the horizontal direction, where he had to infer that the acceleration of the objects would be the same. The problems discussed during the fourth part of the iteration were all set in the vertical direction and student 1's response to the horizontal motion indicates that this student still did not understand the relationship presented by either Newton's second law or the kinematic equations. Student 2 related the force to the velocity in both questions and did not relate the bigger force to the bigger mass, resulting in equal acceleration of the two objects. Student 6 failed to relate the effect of object B's non-zero velocity and equal acceleration when object A starts to move, to the displacement travelled but applied the force to mass ratio in question 6 correctly.

5.6.3.2 Multiple representations: Set B

In this section two students' use of representations in their individual responses to particular questions in the pre-and post-instruction are compared. This individual comparison was done to evaluate their implementing of the conditional statements discussed in the iteration as well as to evaluate to what extent their use of multiple representations has changed from pre- to post-instruction. Student 4's pre-and post- instruction answers on questions 2 and 5 are presented and discussed while student 3's pre-and-post-instruction answers on questions 5 and 6 are presented and discussed (see Figure 5-14).

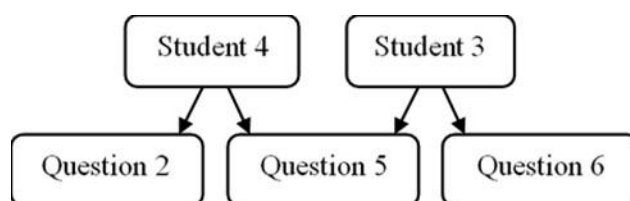


Figure 5-14: Schematic diagram of which students' answers to which questions are discussed

Student 4: Answers on question 2 (Figures 5-15A and 5-15B)

Student 4's pre- and post- instruction responses on question 2 were compared with each other to analyse interpretation of the conditional statements as well as the ability to translate verbal representations into mathematical representations post-instruction. Student 4's answers are presented in Figures 5-15 A and 5-15 B.

In the pre-instruction answer for question 2, Figure 5-15A, Student 4 gave a concise, clear and logical explanation for the answer he chose. The answer indicated understanding of the relationship between the displacements (height h) of the balls and the equal acceleration; that both balls fell the same height in the same time. Because ball A started from a higher height it

meant that A has reached B's original position at the time that B reached the ground. However, Student 4 did not specifically relate the time with the displacement of the balls. In the post-instruction answer, Figure 5-15B, Student 4 successfully used equations (symbolic mathematical form of representation) that related the displacement with the time to present an argument for B reaching the ground before A. In summary student 4 related the time and the displacement by the qualitative use of equations that describe the relationship between time, displacement and acceleration. In both the pre-and post-answers the student correctly indicated equal acceleration for the balls regardless of the difference in their masses, hence I infer that student 4 had no difficulty implementing the conditional statement of disregarding air resistance before instruction.

2. Two balls A and B with different mass are at the same time dropped from different heights. The mass of ball A is twice that of ball B. Ignore the effect of air resistance.

Which ball will reach the ground first?

- a. Ball A,
- ☒ b. Ball B,
- c. Both will reach the ground simultaneously.

Please explain your answer as you would to learners.

Ignoring air resistance Ball B should reach the ground first.

Both balls experience the same gravitational acceleration therefore ball B moving a shorter height should reach the ground first, while ball A will still be at height h above the ground.

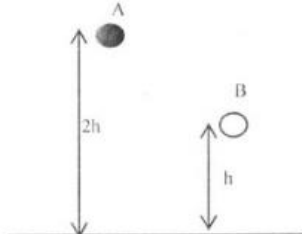
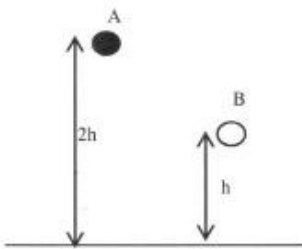


Figure 5-15A: Student 4 Pre-instruction answer on question 2

Which ball will reach the ground first?

a. Ball A,
☒ b. Ball B,
 c. Both will reach the ground simultaneously.

Please explain your answer as you would to learners.



Ball A

$$v^2 = u^2 + 2as$$

$$y = ut + \frac{1}{2}at^2$$

$$2h = 0 + \frac{1}{2}at^2$$

$$t^2 = \frac{4h}{a}$$

$$t = \sqrt{\frac{4h}{a}}$$

Ball B

$$y = ut + \frac{1}{2}at^2$$

$$h = 0 + \frac{1}{2}at^2$$

$$t^2 = \frac{2h}{a}$$

$$t = \sqrt{\frac{2h}{a}}$$

but their acceleration is the same which is equal to g

$$\sqrt{\frac{4h}{a}} > \sqrt{\frac{2h}{a}}$$

Hence ball B reaches the ground earlier than A.

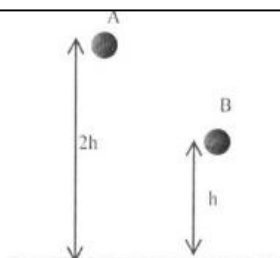
Figure 5-15B: Student 4 Post-instruction answer on question 2

Student 4's answers on question 5 (for question 5 see Table 5-8).

Which ball will reach the ground first?

☒ a. Ball A,
 b. Ball B,
 c. Both will reach the ground simultaneously

Please explain your answer.



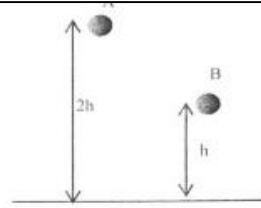
A height h ball A ~~has~~ is already travelling at a far much higher velocity while ball B's velocity = 0. Since they are all accelerating due to gravity, ball A continues to ^{move at} increased velocity hence should reach the ground earlier than ball B.

Figure 5-16A: Student 4 pre-instruction answer on question 5

Which ball will reach the ground first?

- a. Ball A,
- b. Ball B,
- c. Both will reach the ground simultaneously

Please explain your answer.



The balls move the same height after ball B is released

Ball A

$$y = ut + \frac{1}{2}at^2$$

$$h = ut + \frac{1}{2}at^2$$

$$t^* = \sqrt{\frac{2(h-ut)}{a}}$$

Ball B

$$y = ut + \frac{1}{2}at^2$$

$$h = 0 + \frac{1}{2}at^2$$

$$h = \frac{1}{2}at^2$$

$$t^2 = \frac{2h}{a}$$

$$t = \sqrt{\frac{2h}{a}}$$

$$t_A = \sqrt{\frac{2(h-ut)}{a}} < t_B = \sqrt{\frac{2h}{a}}$$

Ball A reaches the ground first since it already has a higher velocity when ball B is released from zero m.s⁻¹. Hence its increased speed makes it cover the height h, in less time compared to B.

Figure 5-16B: Student 4 post-instruction answer to question 5

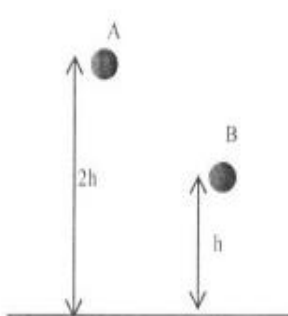
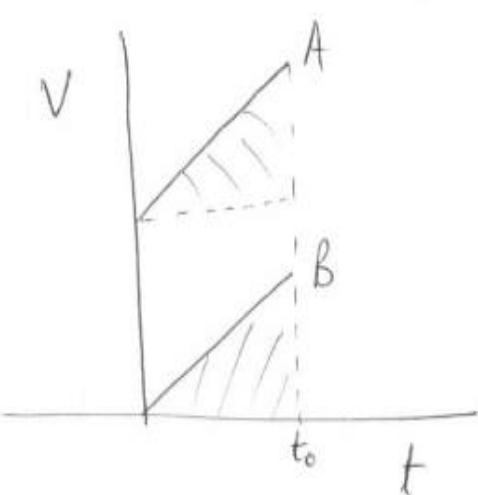
Student 3 pre-and post-instruction answers on question 5 are presented in Figures 5-17 A and B,

5. Two balls A and B with the **same mass** are dropped from different heights and at different times. The initial height of ball A is twice that of ball B. Ball A is released first. Ball B is released at the exact moment that ball A passes ball B at height h . Ignore the effect of air resistance.

Which ball will reach the ground first?

- a. Ball A,
- b. Ball B,
- c. Both will reach the ground simultaneously

Please explain your answer.

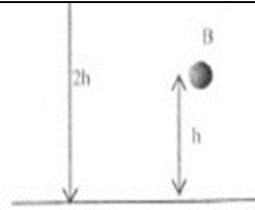



Both balls have the same acceleration, equal gradients.
Both cover equal distances at equal times, but A will reach ground with greater velocity.

Figure 5-17A: Student 3 pre-instruction answers on question 5

- a. Ball A,
b. Ball B,
c. Both will reach the ground simultaneously

Please explain your answer.



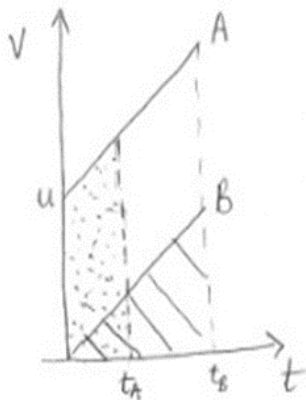
Both ball under free fall, therefore:

$$a_A = a_B = g$$

When both balls are at a height h above ground, ball A has a velocity u and ball B's velocity is zero.

$$\begin{aligned} A: y_A &= ut_A + \frac{1}{2}gt_A^2 \\ h &= ut_A + \frac{1}{2}gt_A^2 \end{aligned}$$

$$\begin{aligned} B: y_B &= ut_B + \frac{1}{2}gt_B^2 \\ h &= 0 + \frac{1}{2}gt_B^2 \\ h &= \frac{1}{2}gt_B^2 \end{aligned}$$



Area under graphs:

$$\text{Area of A at } t_A = \text{Area of B at } t_B = h$$

$\therefore$ from h , both balls cover equal distances, but ball A covers the distance at a shorter time than ball B.
 $t_A < t_B$

Figure 5-17B: Student 3 post-instruction answer to question 5

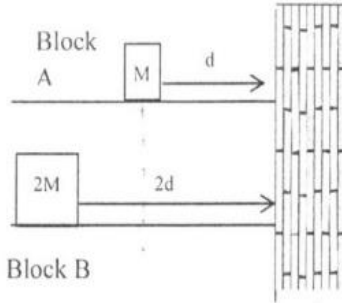
Student 3's pre- and post-instruction answers on question 6 are presented in Figures 5-18A and B.

6. Two blocks, A (mass M) and B (mass $2M$), are accelerated over different distances. The force on block B is twice the force on block A and the distance over which B is accelerated is twice that of block A. Block B is moved first. Block A is moved at the exact moment that block B passes block A at distance d . Friction can be neglected. Which block will reach the wall first?

(a.) Both will reach the wall simultaneously.

b. Block A

c. Block B

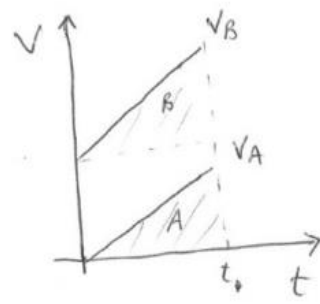


Reason:

$$F_B = 2F_A$$

$$m_B a_B = 2m_A a_A$$

$$2Ma_B = 2Ma_A$$

$$\therefore a_B = a_A$$


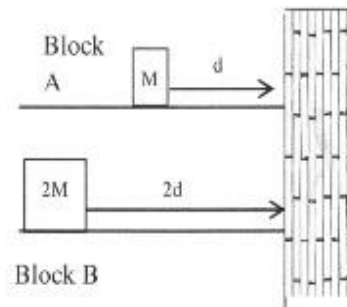
From the graph: gradient of B = gradient of A
Area B = Area A
 $t_B = t_A$

$\therefore$ Two blocks cover equal distances at equal times, but Block B will reach the wall with a greater velocity than Block A.

Figure 5-18A: Student 3 pre-instruction answer to question 6

Student 3: Question 6 Post-instruction answer

6. Two blocks, A (mass M) and B (mass $2M$), are accelerated over different distances. The force on block B is twice the force on block A and the distance over which B is accelerated is twice that of block A. Block B is moved first. Block A is moved at the exact moment that block B passes block A at distance d . Friction can be neglected. Which block will reach the wall first?



- a. Both will reach the wall simultaneously.
b. Block A

☒ c. Block B

$$m_B = 2m_A$$

$$F_B = 2F_A$$

$$m_B a_B = 2m_A a_A$$

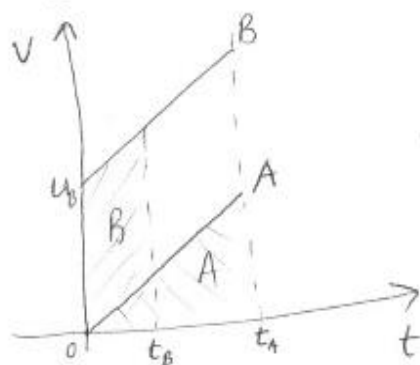
$$2M a_B = 2M a_A$$

$$\therefore a_B = a_A$$

When both blocks are at a distance d from the wall:

$$\begin{aligned} A: \quad x_A &= u_A t_A + \frac{1}{2} a_A t_A^2 \\ x_A &= 0 + \frac{1}{2} a_A t_A^2 \\ d &= \frac{1}{2} a_A t_A^2 \end{aligned}$$

$$\begin{aligned} B: \quad x_B &= u_B t_B + \frac{1}{2} a_B t_B^2 \\ d &= u_B t_B + \frac{1}{2} a_B t_B^2 \end{aligned}$$



Both blocks cover equal distances (d), the area under graph for B is equal to area under the graph for A

$\therefore$ B will cover the distance d within a shorter time (t_B) than A (t_A)

Figure 5-18B: Student 3 post-instruction answer on question 6

Discussion on student 3s' pre-and post-instruction use of multiple representations for questions 5 and 6

Student 3's use of graphs was quite unexpected (Refer to Figures 5-17 A & B, as well as Figures 5-18 A and B). The student related the slope of the graphs to the acceleration which indicated that he knew or understood (it is difficult to determine which) the link between the slope of a velocity-time graph and the acceleration. However, the student did not explicitly state that ball A will reach the ground (or wall) first in Questions 5 (and 6) in the pre-tests, he left it for interpretation by the reader. Although he drew the two motions on the same coordinate system, he did not fully interpret the effect of the non-zero initial velocity on the displacement covered in the pre-instruction answer (Figures 5-17A and 5-18A). From the graph in Figure 5-18A, pre-instruction, it seemed that student 3 only considered the velocity of the balls for the part of the motion where the balls travelled together. In Figure 5-18B, post-instruction, the student indicated that both the time and the velocity will differ for the part of the motion where the balls travel together. It seems that the concept of displacement being represented by the area under the velocity-time graph was clarified by relating the motion diagrams to the displacements covered and ultimately to the graphs. When placing the motion diagrams that indicated equal acceleration for the balls alongside each other, it was clear to see that ball A, having the bigger velocity at the height h which resulted in bigger displacement per time unit than ball B, will fall the remaining height in less time.

5.7 Reflection on the teaching sequence

Reflection on the teaching sequence is given in terms of answering the detailed research questions for this iteration. Regarding the first question: To what extent does clarification of the statement "in the absence of air resistance and friction contribute to student understanding of the net force and the acceleration associated with net force?", the results pointed towards the desirability of interpreting conditional statements that are used to simplify everyday contexts in physics instruction and the consequences of such statements (design principle 2, p. 50). Disregarding the effect of air resistance and/or friction affects the concept of net force and as a result, also the acceleration associated with the net force. Due to the nature of the pre-post questions that focussed specifically on the use of multiple representations, evidence for the effect of explaining the conditional statement of "in the absence of air resistance" from this iteration needed further investigation.

The effectiveness of relating the affordances of different representations of kinematic questions on the other hand, was very clear (design principle 4, p. 50). In particular, linking the affordance of motion diagrams to those of graphs and equations seemed to enhance conceptual coherence of multiple representations and also served to assist qualitatively reasoning on the relationships

represented by kinematics equations. The results on relating various representations with one another revealed other difficulties that student experienced, for example, relating verbal representations with relevant physics equations persisted, and to correctly represent the force-mass-acceleration relationship in terms of proportionality.

A few further relevant aspects that were revealed in the course of this iteration are discussed in more detail below.

5.7.1 Building on previous knowledge

Explaining conditional statements served to clarify the idealized theoretical situations implied, for example in definitions of Newton's first and second laws (design principle 2, p. 50). By clarifying the affordance of ignoring the effect of air resistance and friction, understanding of physics concept of net force is enhanced. Instead of merely attempting to substitute alternative conceptions with the correct ones, i.e. attempt the "fix it" or "refute and replace" approach, student everyday experiences were validated and used in teaching, the "work with it view" (Duschl *et al.*, 2011). This approach allows students to make sense of the new conception by viewing it in the context of their present knowledge and understanding, thus reconciling the new conception with their existing conception (Hewson, 1982). Building on existing knowledge is aligned with the constructivist theory of learning whereas attempts to refute and replace students' conceptions are not. Developing conceptual understanding is not "established" by presenting students with correct conceptions, conceptual understanding is more complex and difficult to accomplish. The extensive literature on both alternative conceptions and conceptual change gives very strong support to the position that a conception that is the target of teaching for understanding (the preferred conception) is related to the existing alternative conceptions" (design principle 1, p. 50).

5.7.2 Transferring verbal representations into mathematical representations

Although the ability to give clear verbal responses/explanations appears to be a pre-requisite for translating verbal representations into mathematical/symbolic form, i.e. equations, correct verbal responses do not always result in correct symbolic representations. This seems likely to be especially true for fractional and/or inverse proportionalities. The difficulty to translate verbal or graphic representations of a problem to equations, and interpret the relationship between the relevant physics quantities, appears to be widespread amongst physics undergraduates (see literature review Section 2.4.6).

5.7.3 Coherence of physics concepts and enhancing understanding of conceptual relationships

The POE and Phenomenon Based Learning protocols were most useful in revealing alternative conceptions, whilst also providing opportunities for linking and discussing the relationships between different applicable physics concepts and thereby enhancing coherence. Linking the affordances of multiple representations combined the affordances of those representations. For example, implementing motion diagrams allowed for visualizing and comparing the motion of paired items for qualitative conceptual reasoning. Relating motion diagrams to the displacements of objects afforded interpretation of graphs and also countered the conception that “doing physics” consists of solving problems numerically.

The consequence of incorporating the simplification statement of disregarding air resistance was highlighted. The key factor here is to explain what the consequences of the simplification “in the absence of air resistance” are. For example, when air resistance is disregarded, objects will fall with equal acceleration, i.e. their motion diagrams will be identical regardless of their mass. Consider two objects of different mass released to fall from different heights at the same time in the absence of air resistance; with the heavier object released from the higher height. Students often predict that the objects will reach the ground at the same time or even that the heavier object will reach the ground first. However, by placing the identical motion diagrams alongside each other on the pictorial representation, the equal gravitational acceleration can be visualized and other variables such as displacement and velocity, for example, can be compared qualitatively. When an appropriate kinematic equation is related to the information made visible by the motion diagram, the relationships between the various physics quantities become much clearer.

5.7.4 New insights that will be incorporated in the design for the next iteration

The results of the teaching sequence that comprised this second iteration informed the subsequent iterations of the DBR (Section 3.5.2). To investigate the influence of clarifying the conditional statement “in the absence of resistive forces”, the net force concept applied in iteration 2 was expanded to a perspective of acceleration as the net force to mass ratio (design principle 3 (identifying core concepts) for iteration 3). A conceptual approach was developed to introduce and teach acceleration from a non-mathematical perspective. The next iteration in the research cycle, iteration 3, specifically focused on the conditional statement of ‘in the absence of air resistant and/or friction’ (design principle 2) and introducing teaching acceleration from a conceptual qualitative approach, the net force to mass ratio approach (design principle 3).

CHAPTER 6: ITERATION 3 - A CONCEPTUAL APPROACH TO TEACHING ACCELERATION

6.1 Introduction

In this chapter I present a report on the teaching experiment which was implemented with third year pre-service teacher education students of Physical Sciences Education at a university in South Africa. The teaching experiment that was designed as and implemented in this third iteration of the DBR was a logical next step resulting from the previous iteration. It consisted of both the traditional mathematical approach to acceleration as the ‘time derivative of velocity’ and an alternative conceptual ‘force to mass ratio’ approach to acceleration.

The instructional sequence was designed with the intent to expose student missing conceptions (see Section 2.2.5), to determine their level of conceptual understanding of acceleration before and after the teaching experiment and to determine student perceptions of this intervention. In the community of pre-service teacher education students who participated in this study, it is important to address issues that are known to cause difficulties in understanding of core concepts, such as acceleration.

It is important to note at the outset that while these were prospective teachers of Physical Sciences, their involvement in this iteration of my DBR was very much as students of mechanics (as shown by data collected in the iteration) – their understanding of the concepts of focus in my research was as inadequate as any other group of students who had completed High School Physical Sciences.

6.2 Research question for the third iteration

The detailed-research question guiding this iteration was: What is the effect of a conceptual teaching approach to acceleration as the net force to mass ratio on student understanding of i) the concept of acceleration, and ii) the qualitative use of proportional relationships in terms of Newton’s second law?

The purpose of this iteration of the DBR was to make the difficult concept of acceleration accessible and meaningful to physics students. This is in accordance with design principles 3 and 4 as described in Section 3.4.2, in brief ‘core concepts’ and ‘coherence’. Literature of particular relevance to this iteration is found in Sections 2.2.3 and 2.4.2.

It was decided to still focus on one-dimensional situations in this iteration because it is a logical assumption that this situation needs to be understood before two- and three- dimensional motions

can be attempted. To develop different ways of experiencing the one-dimensional situation, all of horizontal (Ferreira, 2014), vertical (Ferreira & Lemmer, 2016) and inclined plane situations were used. This was done in accord with the claim that "an essential part of learning a concept is to develop different ways of experiencing it and to develop understanding requires many different representations of the concept and links to different representations" (Pendrill, 2008:185).

6.3 Research design

For this iteration an exploratory concurrent mixed method research design was followed. Figure 6-1 is a schematic representation of the design. In this design the qualitative and quantitative data were collected concurrently and the two methods used to confirm or cross-validate findings within the study.

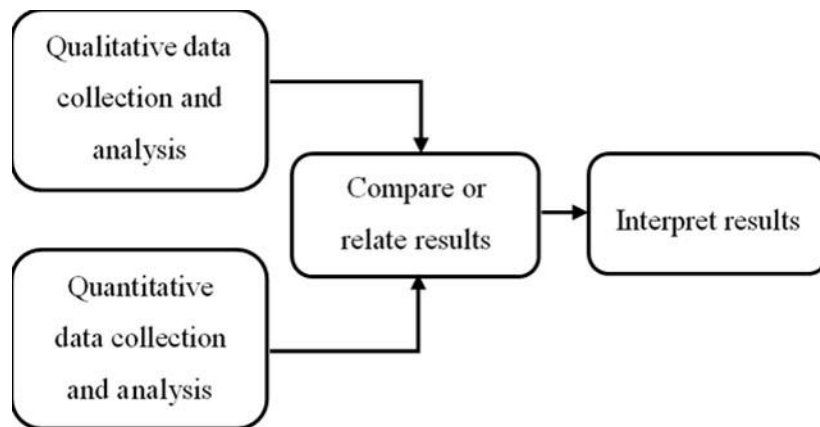


Figure 6-1: Schematic representation of the exploratory concurrent mixed method research design

6.4 The teaching experiment

The time derivative of velocity approach (hereafter called the mathematical approach) to teaching the concept of acceleration was included in the teaching experiment as this approach is used in most South African schools. In the alternative approach also used in the experiment (hereafter called the qualitative approach), proportional reasoning came as a consequence of considering acceleration as the net force to mass ratio. The entire teaching experiment was presented as practical activities following the Predict-Observe-Explain protocol. The teaching experiment was developed as methodology with the purpose that students "experience, first hand" (Steffe & Thompson, 2000:267) qualitative mathematical reasoning in the context of acceleration. One aim of this third iteration was to gain a deeper understanding of student qualitative reasoning in the context of acceleration as a result of the sequence of tasks and activities developed to enhance qualitative conceptual understanding of acceleration in one-dimensional contexts. The use of

multiple representations can support the construction of understanding (Ainsworth, 2008; Linder, 2009). The ability to construct and switch between multiple representations of a domain has been identified as fundamental to successful learning (Spiro & Jehng, 1990). Insight achieved in this way increases the likelihood that learning will be able to be transferred to new situations (Bransford & Schwartz, 1999).

The teaching experiment on Newton's second law was presented in two practical sessions consisting of a total of five sequential activities. Four of the activities, all included in Practical Session 1 as indicated in Figure 6-2 below, focused on acceleration along an inclined plane; the fifth activity, Practical Session 2, focused on vertical downward motion. Figure 6-2 below represents the sequence of the teaching experiment.

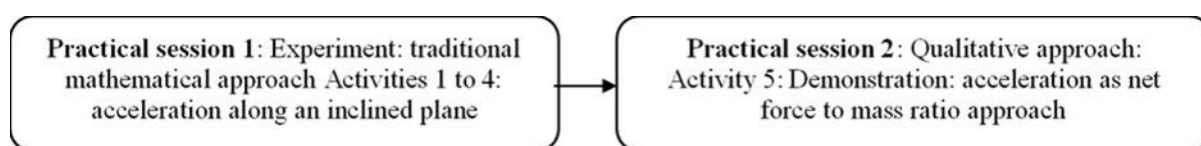


Figure 6-2: Schematic presentation of teaching experiment

Figure 6-3 is a diagrammatic representation of the four activities that made up practical session 1. Each activity had accompanying worksheets to be completed by the students (see Appendix H).

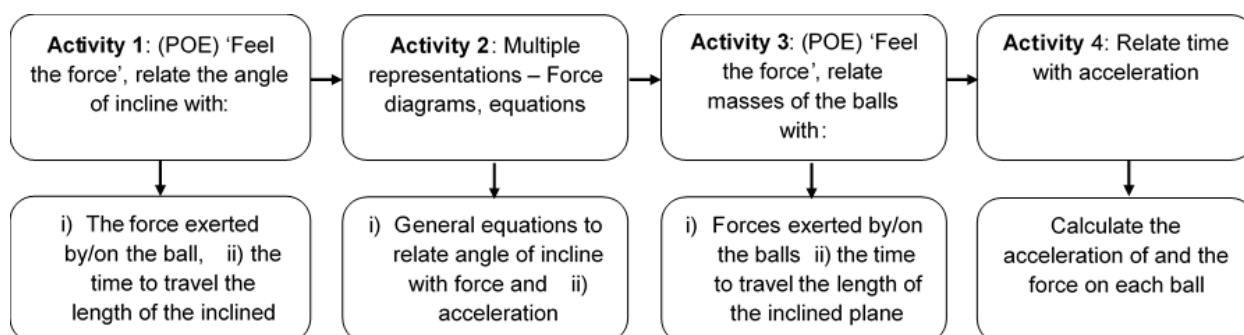


Figure 6-3: Activities in Practical session 1 of the Teaching experiment

Activities 2 and 4 followed the mathematical approach to teaching net force and acceleration, as was done in Iteration 2 Part 3a Activity 2 (see Chapter 5). This approach entails that equations are inferred and are used to calculate the numeric value of the quantity under consideration (Activity 2) or using equations to obtain numerical values for physics quantities (Activity 4). Activities 2 and 4 are typically included in the Further Education and Training (FET) band (grades 10 to 12) for Physics as part of the CAPS. In Activity 1 of the first practical session of the teaching experiment, the students did a qualitative experiment to relate the force acting on/ exerted by a ball rolling down an inclined lane, using sensory experience as qualitative force measure (how hard the ball hit their hands), and how this varied with change in the angle of incline. (The experiment described in Activity 1, Part 3A of Iteration 2, was repeated here). Another intent of

Activities 1 and 3 was to use sensory measurements as an introduction to qualitative experimentation. For Activity 2 the students executed an experiment based on the mathematical approach to acceleration of balls with different mass as the time derivative of velocity. Figure 6-4 represents the mathematical approach to determine the acceleration of objects along an inclined plane in Activity 2. Figure 6-4 also presents the core ideas underlying Activities 3 and 4.

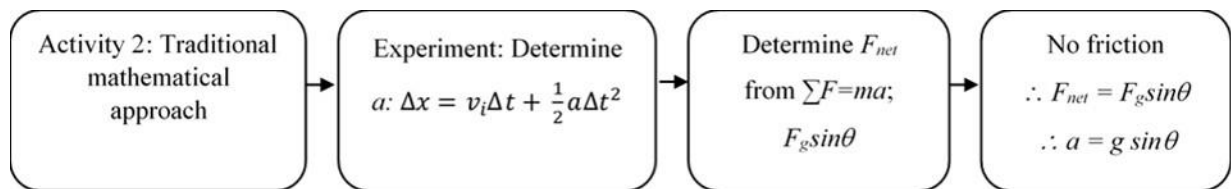


Figure 6-4: Steps in the mathematical approach to determine acceleration along an inclined plane

Two activities (1 and 3) in practical session 1 as well as the activity in practical session 2 followed a Predict-Observe-Explain (POE) protocol (White & Gunstone, 1992). This required that the students predicted the outcome of the activity and gave reasons for their predictions, executed the activity and compared their observations with their predictions. Different ways of experiencing the one-dimensional vertical and inclined plane situations were incorporated in the teaching experiment, for example, in addition to executing the experiment with the mathematical and the qualitative approaches, a video clip on falling objects was shown after the demonstration.

Practical session 2 consisted of the fifth activity in the teaching experiment, a demonstration of different sets of falling objects that invited explanation of acceleration in terms of the ratio of the net force exerted on an object to the mass of the object. Activity 5 was a repetition of Part 3B of Iteration 2, but with an elaborated explanation regarding the magnitude and the effect of air resistance on falling objects, developed in collaboration with Gunstone (2016). The explanation included a qualitative conceptual focus on the alternative approach to acceleration as the net force to mass ratio. The POE protocol was followed once again for the demonstration involving two balls of the same size but different mass, and the demonstration involving two sets of paper cups with different mass, each pair released from the same low height respectively (Figure 5-5). Due to time limitations the students completed only the Predict and Observe parts after which I presented the Explanation using prepared PowerPoint slides. The core aspects of the explanation are reproduced and presented with the worksheets for this iteration as Appendix H.

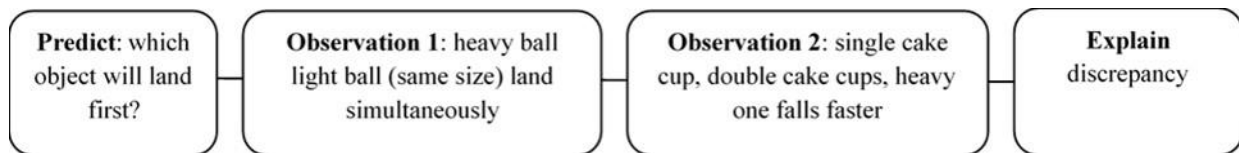


Figure 6-5: Predict-Observe-Explain protocol for the demonstration in Activity 5

The purpose of the demonstration was to show that heavier objects are not always observed to fall faster. The cognitive dissonance created by the demonstration served as an introduction to explain the extent to which factors such as mass and falling height would determine whether the effect of air resistance would be observable or not, with the dimension of qualitative reasoning also added. This was done by focusing on the equation representing Newton's second law not only as a tool of numeric calculation but also as an expression of the relationship between the three physics variables of force, mass and acceleration, an approach also consistently advocated by Redish (2014:538; 2017:5). The explanation part of the POE protocol provided the opportunity to link various concepts related to acceleration and force such as the relationships represented in kinematic equations.

Figure 6-6 below is a representation of the procedure of the explanation that followed the demonstration. The equation for air resistance was used to qualitatively compare the effect of air resistance on objects of different masses. This was followed by using force diagrams to explain the concept of terminal velocity and to highlight the significance of the height from which objects fall for observation of the phenomenon of air resistance.

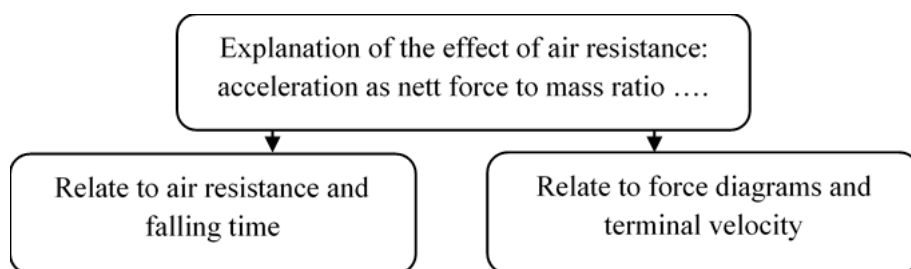


Figure 6-6: The two components of the explanation on the effect of air resistance

In the final part of the experiment the students were asked to reflect on the teaching experiment by giving their perceptions of the effect of the alternative qualitative approach as the net force to mass ratio as compared to the traditional mathematical time derivative of velocity approach.

6.5 Participants

A cohort of third year Physical Sciences Teacher Education students (N = 24) enrolled for a B.Ed. Further Education and Training (FET) qualification from a South African university participated in the study. The experiment was conducted as part of their 'Methods of Teaching Physical

Sciences' module. Physical Sciences consists of both Physics and Chemistry and is offered in the last three years of high school (the FET band) in South African schools. The number of participants in the various data collection stages of these practical sessions differs because of variable student attendance (a common matter in this post-school educational context). Only twelve of the students (N=12) participated in both tests and fourteen (N = 14) students offered explanations for their answers in the delayed-post-test. There is no evident reason for the data from these students having systematic differences from the remainder of the cohort.

6.6 Research instruments

The results obtained from three instruments are reported here, namely a pre- and delayed-post-test questionnaire, student reflections on the teaching experiment and the explanations the students gave for their answers in the delayed-post-test questionnaire. The questionnaire is attached as Appendix G, a summary of student explanations is presented in Table 6-3 and a summary of student reflections is presented in Table 6-6 as part of the data analyses and discussion below (see Section 6.9).

6.6.1 Pre- and delayed-post-test questionnaire

A shortened version of the diagnostic questionnaire developed for and implemented in the second iteration of the DBR reported in Chapter 5 was used as the pre and delayed-post-test (included as Appendix I). Item 1 of the Force Concept Inventory (Hestenes *et al.*, 1992), validated for use in high school through university level non-quantitative assessment (Savinainen & Scott, 2002), was used as the base question. Variants of the base question were self-compiled and included in the pre- test, with the direction of motion and /or the variable to be solved systematically varying from the base question (Cronbach's Alpha = 0.7).

The qualitative pre-test questionnaire consisted of seven multiple choice questions set in different directions of motion and with different physics quantities to be solved (attached as Appendix G). Questions 1, 2, 3 and 4 were included to investigate student ability to implement the velocity-displacement-time relationship with acceleration in different directions of motion (upwards, downwards and at an angle). A further three questions focused on the force to mass relation of Newton's second law (Questions 5, 6 & 7). The same questionnaire was given as a delayed post-test two months later, with the requirement that the students now also gave reasons or explanations for their answers, in an open-ended format; hence the delayed-post-test data represent post-instruction *retained* understanding.

The questions are summarised in Table 6-1. To indicate the context of the question, an arrow indicating the direction of motion was paired with the physics quantity to be solved. For example,

in the key ' $\nearrow d$ ', the arrow represents upwards movement on an inclined plane with d , the magnitude of the displacement, the physics quantity to be solved. A summary of the students' explanations given on the delayed post-test is presented in Table 6-3 Section 6.9.2.2.

Table 6-1: Summary of context of questions in pre-delayed-post-test questionnaire

Question	Context	Displacement	Size of balls	Masses
1	$\downarrow t$	Same	Same	Differ (3x bigger)
2	$\searrow t$	Same	Same	Differ
3	$\uparrow v$	Same	Same	Differ (2x bigger)
4	$\nearrow d$	Same	Same	Differ
5	$\downarrow F$	Same	Differ	Differ (half)
6	$\downarrow F_{net}$	Same	Same	Differ
7	$\uparrow F$	Same	Same	Differ (2x bigger)

6.6.2 Student reflections

Students were asked to reflect on the influence the teaching experiment had on their understanding of the concept of acceleration and present their reflections by answering specific questions on the teaching experiment. These are also summarized in Table 6-6.

6.7 Purposes of data collection

The results of the pre-test to determine the level of understanding developed as a result of the Physical Sciences teacher education students' schooling and university learning prior to the experiment served as baseline for the experiment. The answers to these items were not provided to or discussed with the students after the pre-test. The delayed-post-test with explanations, as well as the student reflections, were used to determine the impact and extent of the teaching experiment on the student understanding in unfamiliar contexts. The explanations that the students offered allowed me to evaluate their level of understanding according to a coding system explained in Section 6.9.2.2. Figure 6-7 represents the sequence in which the data were collected.

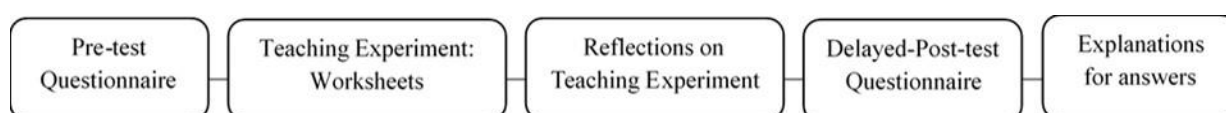


Figure 6-7: Sequence of data collection for third iteration

6.8 Data analysis

Because of the small number of students for whom complete data sets were obtained, usual statistical analyses would be essentially impossible to interpret, therefore I used average normalised gain (Hake, 1998) as an assessment of the effectiveness of the teaching experiment in promoting conceptual understanding. Content analysis was done on the qualitative data - student explanations for the delayed-post-test answers and student reflections on the intervention were each analysed, coded to determine trends and interpreted to obtain information on the effect of the alternative qualitative approach to acceleration.

6.8.1 Quantitative analysis

Twelve students participated in both pre-and delayed-post-tests and their responses to the multiple choice questions were analysed to establish the normalised gain for each of the questions in the qualitative diagnostic test. The average normalised gain ($\langle g \rangle$) is claimed to represent the degree of progress of the students and indicates the effectiveness of the intervention and is calculated as

$$\langle g \rangle = \left(\frac{\text{post-test score} - \text{pre-test score}}{100 - \text{pre-test score}} \right) \text{ (Hake, 1998).}$$

The achievement of the students on the pre-delayed-post assessments and the $\langle g \rangle$ scores are summarised in Table 6-2.

6.8.2 Qualitative analysis

The qualitative data that were collected are discussed in the following two sections.

6.8.2.1 Student reflection questions

In accordance to commonly used practice at universities, the students were asked to evaluate the teaching practice of this teaching experiment by reflecting on the influence that the conceptual part of the teaching experiment had on their *own* understanding of the concept of acceleration, compared to the traditional mathematical approached which was familiar to them. To provide structure to the reflections they were asked to formulate their reflections in terms of answering specific questions on the teaching experiment and to indicate why they gave the answer they did. These reflections were read carefully a number of times and common topics and themes were extracted. The topics are presented in Table 6-6 in Section 6.9.4. The approach and the form of the specific questions were of a nature and format already familiar to the students through the usual teaching evaluations conducted in this university at the completion of each subject semester.

6.8.2.2 Delayed-post-test explanations

Fourteen students provided explanations for their answers in the delayed-post-test; these are summarized in Table 6-3. Because responses to both pre- and delayed-post-tests were given anonymously, the explanatory responses of students could not be linked to a specific student in the pre- delayed-post-test and thus no specific student comparison with the pre-test data could be made. The explanations were analysed to identify any additional 'missing conceptions' that were still evident after the completion of the teaching experiment and to determine the level of student understanding. Therefore, the conceptions were not only evaluated in terms of their level of understanding but also interpreted in terms of the context of the question.

Correct explanations were evaluated and coded based on presence or absence of student reference to the correct force to mass ratio, equal acceleration and proportional reasoning. A further distinction was made between correct answers in terms of higher and lower levels of understanding. For example, explanations indicating that students used proportional reasoning linking different physics quantities (using or implicating equations in symbolic form) were considered to indicate a higher level of understanding than explanations which referred only to the (correct and appropriate usage of) force to mass ratio. Explanations stating only equal accelerations as reason were considered to indicate a low level of understanding. This is explained in detail when these data are presented and discussed in Section 6.9 below.

Unsurprisingly, the incorrect explanations covered a larger variety of topics. Explanations implying that heavy objects fall faster (and/or at a higher rate); failure to identify the relevant force; incorrect use of inverse relations and contradictive reasoning were identified. 'Explanations' merely stating the conditions (e.g. in the absence of air resistance objects fall at the same rate) were considered to be incorrect and also of low quality. Furthermore, the incorrect explanations which contained opposing or incompatible statements were classified as contradictive reasoning. These were distinguished from explanations that contained incorrect inverse relation reasoning where the students i) could not represent their verbal statement with a correct mathematical proportionality or ii) were unable to explain the inverse proportionality clearly.

6.9 Results and discussion of results

6.9.1 Discussion of results of practical session 1

This part of the teaching experiment did not meet my expectations at all. The student data for the mathematical approach (Practical session 1 of this iteration) were collected in a real teaching context using low-level technology measuring equipment, e.g. protractors, rulers, stopwatch facilities on cell phones. These data were often unconvincing, for a number of reasons. Firstly, I

made assumptions regarding the students' level of mathematical competence which the results proved were unfounded. Secondly, the inadequacies of the measuring equipment combined with inaccurate measurement of the different variables by the students produced massive problems in terms of 'useable' data. My attempt to improve conceptualisation of the experiment by providing a "good set of data" caused unexpected confusion on the students' part about which data they should use and hence impacted negatively on the validity of the experiment. Reflection on this disappointing experience lead me to reconceptualise the forms of observation one might use for falling bodies and/or motion along inclined planes.

6.9.2 Results of practical session 2

6.9.2.1 Quantitative results: Student achievement in qualitative pre-test

To establish whether the intervention promoted better conceptual understanding, student performance on the qualitative test prior to the teaching experiment was compared to performances on the delayed- post-test two months after teaching. Table 6-2 summarises the responses of the students in both these tests and gives the normalised gain.

The results indicate positive average normalized gains in questions 2, 5, 6 and 7 ($\langle g \rangle > 20\%$); no progress in question 1; and negative normalized average gains in questions 3 and 4 ($\langle g \rangle < 0\%$). The highest positive gain was for question 6 ($\langle g \rangle = 40\%$), followed by question 5 ($\langle g \rangle = 33\%$), question 2 ($\langle g \rangle = 22\%$); and question 7 ($\langle g \rangle = 20\%$). Three of these four questions (numbers 5, 6 and 7) were in the more familiar context of vertically up and vertically down motion.

Table 6-2: Number and percentages of correct answers for pre- and delayed-post-tests, and average normalised gain

Question	Context	Pre-test N	% Pre-test	Delayed- post-test N	% Delayed- post-test	$\langle g \rangle$ % pre-delayed- post-test gain
1	↓t	7	58.3	7	58.3	0
2	↘ t	3	25.0	5	60.0	47
3	↑v	4	33.3	3	25.0	-13
4	↗ d	3	25.0	2	16.8	-11
5	↓F	9	75.0	10	83.3	33
6	↓F _{net}	7	58.3	9	75.0	40
7	↑F	7	58.3	8	66.7	20

Questions 5 and 6, with percentages correct answers of 75% and 58% respectively in the pre-test, showed high percentage gains. For question 7, set in upward direction, a positive gain is also noticed. These results indicate that the net force to mass ratio approach had a positive influence on student interpretation of and response to the questions where force was the variable.

In question 2 the students had to compare the travelling time of two objects of different mass moving from rest downward along a frictionless inclined plane. The question not only required students to use the net force to mass ratio, but also to apply the effect thereof in other contexts (i.e. different directions). Although question 2 showed the highest normalized gain, this came from a very low base (only three of the 12 students gave the correct answer in the pre-test, increasing to only five correct in the delayed-post-test). It seemed that the net force to mass ratio approach was less successful in this more complex context than where only the ratio had to be applied.

Questions 3 (vertical) and 4 (inclined) motion were both set in upward direction, with velocity and displacement as the respective variables. The negative normalized average gain observed with both questions 3 and 4 is noteworthy. This indicates that the student difficulties with implementing the velocity-displacement-time relationship with acceleration in different directions of motion (upwards, downwards and at an angle) were not diminished in this iteration, by the net force to mass approach. Questions involving motion in different directions and planes were included in the next iteration of the study, reported in Chapter 7.

Although the results suggest an overall improvement in four of the seven items ($\langle g \rangle > 20\%$) conclusive inference cannot be drawn about this effect due to the small test sample. Analysis of student answers also shows that some who had questions correct in the pre-test gave the wrong answer in the delayed-post-test e.g. the test scores on items 3 and 4 notably decreased in the delayed-post-test. The influence of the teaching sequence can be better understood by analysing the qualitative data obtained from the student explanations supplied for each multiple choice answer and by considering the student reflections on the intervention.

6.9.2.2 Qualitative results

6.9.2.2.1 Physical Sciences teacher education students' explanatory responses given in the delayed-post-test

The explanations were first categorized as correct, incorrect and no explanation. The correct and incorrect categories were further divided in terms of common trends which were identified from multiple readings of these. A summary of student explanations is presented in Table 6-3.

Table 6-3: Summary of explanatory responses in the delayed-post-test

Explanations	Q1 ↓ t	Q2 ↘ t	Q3 ↑ v	Q4 ↗ d	Q5 ↓ F	Q6 ↓ F _{net}	Q7 ↑ F
Total: correct explanation	9	6	3	2	11	12	11
F/m ratio correct	4	3		1	11	6	2
Equal acceleration	3	1	1				
Proportional reasoning	2	2	2	1		6	9
Total: incorrect explanation	5	8	11	11	3	2	2
Heavy objects fall faster/ Gravity has larger effect on heavier objects moving upwards	2	3	4	11			
Equal force/ Confusion regarding what force	1	2	6		1	2	2
Conditions as reasons		2					
Alternative inverse relation reasoning (incorrect math relationship)/ Contradictive proportional reasoning	2	1	1		2		
No explanation				1			1

The alternative conception of heavier objects falling faster was sometimes stated differently for upwards and downwards motion. For vertical downward motion the explanation was commonly stated as “heavy objects fall faster” while for vertical upwards motion it was usually stated as “Gravity has bigger effect on heavy objects moving upwards therefore the downward acceleration will be bigger”. Although the explanation “This means the bigger mass has a bigger downward acceleration therefore it reaches a lower height” reveals the alternative conception, it also linked the different physics quantities, and was interpreted as an indication of the student’s attempt to use proportional reasoning.

6.9.2.2.2 Explanations for answers given in the delayed-post-test, in terms of direction

A more fine-grained analysis of the student explanations for choosing a particular answer for the questions was done by grouping the responses according to the direction of movement. In Table 6-4 student responses to four questions (questions 1, 2, 5 and 6) representing vertical/inclined downward movement with different variables (time and force) are compared.

Table 6-4: Responses for questions focusing on various variables in the context of downward, vertical/inclined motion

Explanations	Q1 $\downarrow t$	Q2 $\searrow t$	Q5 $\downarrow F$	Q6 $\downarrow F_{net}$
Total: correct explanation	9	6	11	12
F/m ratio correct	4	3	11	6
Equal acceleration	3	1		
Proportional reasoning	2	2		6
Total: incorrect explanation	5	8	3	2
Heavier objects fall faster	2	3		
Equal force (e.g. velocity is the same because the force of gravity on them is the same / F_g is equal on both)	1	2	1	2
Conditions as reason		2		
Contradictive reasoning	2	1		
Alternative inverse proportional reasoning			2	

Questions 5 and 6 both concerned force as a variable. These two questions had the most high-quality explanations, judged in terms of use of the appropriate ratio and proportional reasoning. A missing conception identified from the explanations was the perception of some students that falling objects experience the same force of gravity (in magnitude) instead of equal gravitational acceleration. The same conception was also present in some responses to questions 1 and 2. For questions 1 and 2, which required relating the force to mass ratio to other kinematic variables, the number of high quality answers (in terms of proportional reasoning) was half that of the other two questions. Incorrect answers and explanations for questions 1 and 2 also revealed the persistence of the notion that heavy objects fall faster. This was in contrast to the explanations that contained contradictive or incorrect reasoning, and/or restated the conditions of the problem statement, and/or showed inconsistencies in students' train of thought resulting in incoherent reasoning.

Questions 3, 4 and 7 focused on vertical or inclined upwards motion with different variables (velocity, displacement and force). These questions were grouped and compared in terms of student explanations, as presented in Table 6-5.

Table 6-5: Responses for questions focusing on various variables in the context of vertical upwards and inclined upwards movement at an angle

Explanations	Q2 $\downarrow t$	Q3 $\uparrow v$	Q4 $\nearrow d$	Q7 $\uparrow F$
Total: correct explanation	6	3	2	11
F/m ratio correct	3		1	2
Equal acceleration	1	1		
Proportional reasoning	2	2	1	9
Total: incorrect explanation	8	11	11	2
Heavier objects fall faster / Gravity has larger effect on heavier objects moving upwards	3	4	11	
Equal force	2			2
Conditions as explanation	2			2
Contradictive reasoning	1	1		
Incorrect Inverse relation reasoning (incorrect math relationship)				
Confusion regarding force		6		
No reason provided			1	1

The majority of the students had question 7 correct (vertical upward motion with force a variable) and all those students gave high quality explanations for their answer. Two explanations were consistent with the correct answer even though the students' answers to the question were incorrect. Almost all of the students who had questions 3, 4 and 7 correct offered high quality explanations using proportional reasoning relating the different physics quantities, either by means of equations or applying the force to mass ratio correctly.

The incorrect explanation offered mostly for question 4 (upward motion on an inclined plane) and to a lesser extent for question 3 contained the alternative conception of gravity having "a bigger effect" on heavy objects moving upward, which corresponds with the notion of heavy objects fall faster. The incorrect explanation that appeared the most times for question 3 was the one that indicated that the wrong force was considered, confusing the force experienced by the object while moving upwards with the force needed to propel the object into the air.

6.9.3 Discussion of qualitative results

The results indicate that the net force to mass ratio teaching approach had a positive influence on student answers regarding the gravitational force to mass ratio in downward motion and in upward motion where force was the physics variable to be considered. It appears that the net

force to mass approach facilitated learning in terms of the force-mass-acceleration relationship, but has less impact on performance on problems which required inference in linking different physics quantities. The number of students who either used the ratio correctly or applied proportional reasoning relating different physics quantities in equations indicated that it may be helpful to further investigate the impact on student learning of using this approach.

Unfortunately, the results also revealed missing conceptions that need to be addressed. One such concept, still 'missing' after the students experienced the teaching sequence, was that in the absence of friction and air resistance, objects moving along an inclined plane were subjected to the (component of) gravitational force as the net force acting on them and the motion was therefore to be interpreted in the same way as for any other direction of motion. While the teaching experiment appears to have succeeded in improving some aspects regarding understanding of up- and downward motion, the same cannot be said about inclined motion.

Another concept that needs clarification is the identification of the forces involved in projecting an object into the air. Some students could not distinguish between the force required to project an object into the air and the force/s acting on an object whilst moving through the air. Confusion in terms of identifying the correct force was noticed in student explanations for question 3 and classified as such. Some students argued that the bigger mass needed a bigger force to be projected upwards; however, question 3 was in terms of the net force experienced by the objects while they were moving upwards *in free fall*. The difference between these forces needs to be emphasized in teaching.

Because physics is easy to teach mathematically, it is assumed to be easy to learn mathematically (Hewitt, 1983). The improvement of student performances on the qualitative (conceptual) test strongly suggests the benefit of a teaching approach that focussed on the force to mass ratio when considering acceleration. Calls for such a conceptual approach have been made since at least the early 1980's. For example, Hewitt (1983:305) asserts that physics "has a reputation that it is incomprehensible". He argues that the fundamentals of physics should not be taught in their traditional mathematical form but in language familiar to students so as to make conceptual understanding more accessible to students.

6.9.4 Reflections of students on the intervention

Four themes were identified in the student reflections. The themes, with examples of student answers, are presented in Table 6-6.

Table 6-6: Student reflections on the influence of the teaching experiment on their conceptual understanding of acceleration

Themes	Representative quotations from students
The F/m ratio approach	From this equation and approach I make reasoning. It improved my understanding of acceleration The qualitative approach helped me as a future teacher to be able to better explain the force to mass ratio without going into mathematical relationships (calculations). The F/m ratio approach brought to my attention to understand the concept of acceleration. Conceptual understanding for the concept acceleration is not explained in meaning full manner (in school) that can help learners to make sense of the acceleration concept in their lives. There need to be a more conceptual explaining before jumping into the experiment
POE teaching strategy	The entire 1 predict, 2 observe, 3 explain approach helped to conceptualize all the information.
Proportional reasoning	Proportionality was learnt. There is an inverse proportionality between the acceleration and the mass of the object. As the mass increases the acceleration will decrease and vice versa. Therefore: $a \propto F$; $a \propto 1/m$; $\therefore a = F/m$
Clarification of Misconceptions	The force to mass ratio approach has broadened my understanding of the concept. It cleared some of the misconceptions I had.

Physical Sciences teacher education students are expected to be able to provide qualitative explanations for why answers to physics problems (such as those posed in the pre-test) are correct or not. Some of the qualitative reasons provided here may stem from these students' experiences with the traditional approach followed by South African schools, as prescribed in the CAPS (Curriculum and assessment policy statement) for South African schools. As one student's reflections noted, most school teachers do not invoke a connection between force and acceleration, pointing toward a possible deficit in teachers' qualitative reasoning skills. The students' reflections after the teaching experiment indicate that while some students' qualitative reasoning skills have improved, some still were not able to express their explanations verbally or as a mathematical relationship (See Table 6-3). I agree with the many physics education researchers (e.g. Hewitt, 1983; White & Gunstone, 1992; Reif, 1995; Turner, 2003) that physics students in general need qualitative problem-solving strategies that would help them recognize the conceptual relationships between the physics variables and enhance their conceptual understanding.

6.10 Conclusion

6.10.1 Addressing the research questions

The conclusions I draw from this iteration are discussed in terms of the two parts of the detailed research question that drove this part of the DBR.

- (i) What is the effect of the alternative teaching approach to acceleration as the net force to mass ratio on student understanding of the concept of acceleration?

The average normalized gains on questions relating only to the force to mass ratio on vertical upwards and downwards motion, considered in conjunction with analysis of the qualitative data, indicate that the alternative approach to acceleration does contribute to improved student understanding of the concept of acceleration.

- (ii) What is the effect of an alternative teaching approach to acceleration as the net force to mass ratio on student understanding of the qualitative use of proportional relationships in terms of Newton's second law?

Even though the participants constituted a relatively small sample, the evidence of growth in pre-delayed-post achievement was promising. The data suggest a positive impact on student use of proportional relationships, but only as far as the net force to mass ratio is concerned. Students also did not always have stable conceptions after the teaching experiment, as evident from the decline in the delayed-post-test compared to the pre-test for some questions.

In questions with different contexts, i.e. for motion along an inclined plane or upwards motion, especially if the variable to be compared was something other than acceleration or time, there was a decline in the correct responses. This may be ascribed to the 'missing conceptions' that were not explicitly addressed in the teaching experiment or it may be that the students did not transfer their new knowledge to these other contexts. Any such lack of transfer could be due to the fact that the students were not familiar enough with the new way of thinking to apply that to different contexts, something which might be expected from extensive prior learning with the traditional mathematical approach. Another possibility is that the students may see kinematic (physics) equations only as means of solving numeric problems and not as expressions of relationships between variables.

The evidence of improved performance in some areas indicates that an explicit focus on acceleration from a force to mass ratio perspective has contributed to concept building in some contexts, more specifically in enhancing students' conceptual qualitative reasoning. The positive results obtained for the force-mass-acceleration relationship from this iteration suggest that there

may be merit in tuition on the use of physics equations as reasoning tools, an idea that occurred to me in the first iteration but which could not be investigated in this iteration due to time limitations. Although considering relationships from a qualitative perspective was new and unfamiliar to these students, data do indicate it to be a very promising prospect worth pursuing in wider contexts. For example, if the net force to mass ratio for two different objects is the same, it means the objects have the same acceleration. Therefore, when the acceleration is the same, the relationships between physics variables represented in kinematic equations can also be inferred with much more ease and without having to do calculations.

The traditional mathematical approach, Practical session 1 in this iteration, was not investigated in the subsequent iterations of this DBR. As pointed out in Section 6.9.1 above, I made assumptions regarding existing student competencies in mathematics and physics which the data on the mathematical experiment showed were likely unfounded.

The overall results from this iteration indicated a positive trend in student conceptual understanding of acceleration as the result of the net force acting on objects with specific mass, i.e. the net force to mass ratio. The advantage of interpreting conditional statements that are used to attempt to simplify everyday contexts (design principle 2, p. 50), as revealed in the second iteration (see Chapter 5), was confirmed. Comparison of student answers to pre- and delayed-post – instruction questions and their reflections on the teaching experiment indicated a positive effect of approaching acceleration from a conceptual net force to mass ratio perspective. Although the improvement in student conceptual understanding of acceleration was promising, more work is required to help students relate different physics quantities through qualitative and/or proportional reasoning.

However, the results further revealed student difficulties in relating relevant physics concepts to motion along an inclined plane, as well as a common lack of ability to apply the force-mass-acceleration relationship qualitatively as was also noted in Chapter 5. In accordance with the argument of Hewitt (1983) and many others, delaying the introduction of quantitative mathematization by first introducing qualitative proportional reasoning for threshold concepts such as acceleration, for example, is therefore recommended.

6.10.2 Implications of the iteration for further study

The difficulties experienced with the traditional mathematical approach to the teaching of Newton's second law initiated the development of simpler (i.e. less technology-dependent and less mathematical) and more effective ways to enhance conceptual understanding of acceleration as a core concept in introductory mechanics that have been reported in this chapter. Following

the results of this iteration, I proposed that a conceptual qualitative (i.e. non mathematical) approach to teaching physics, including using equations as reasoning tools (design principle 4, p. 50) be a strong focus of the next iteration. Questions on motion along an inclined plane, which were very poorly answered in all of the questionnaires used in this iteration of the study, may be used to evaluate the effectiveness of such a conceptual approach.

This iteration has several important implications for consideration of and emphases on design principles that informed the next iteration of my study, namely an approach involving different activities to i) facilitate a better understanding of the concept acceleration; (ii) identify missing conceptions that need explicit tutoring for students, (iii) explain and validate simplifications common in the teaching of physics in terms of linking the real and the physics world and iv) introduce the usage of physics equations as qualitative reasoning tools before mathematization.

The next chapter reports on a tutorial designed to incorporate the findings of this part of the broader study. As per design principles 2, 3 and 4 (p. 50), the tutorial aimed to integrate the real world, physics world and mathematical world using simple real world experiences to develop student proportional reasoning ability and physics-based explanations.

CHAPTER 7: ITERATION 4 - INTRODUCING EQUATIONS AS REASONING TOOLS

7.1 Introduction and research question that drove this iteration

In the previous three chapters, Chapters 4, 5 and 6, the first three iterations of the DBR were described. The first iteration consisted of a questionnaire that was distributed and completed by first year undergraduate physics students in consecutive years to determine the extent of the identified problem while the focus of the second and third iterations was to investigate possible teaching sequences in which the use of conditional statements and alternative conceptions regarding falling objects were respectively discussed. To enhance student understanding of the relationships between physics variables as represented by physics equations, the use of equations as reasoning tools was introduced in the context of Newton's second law. The relationships between physics variables were further developed by combining multiple representations to explain and clarify the effect of neglecting resistive forces on moving objects and to present acceleration as the net force to mass ratio. In the second iteration an alternative approach to acceleration as the net force to mass ratio was investigated in a teaching experiment. In each of these iterations, the previous three and the fourth, I was the teacher implementing the iteration.

The question underpinning this fourth iteration emerged as a logical consequence from the results of the previous iterations: How will an approach consisting of i) an alternative representation of acceleration as the net force to mass ratio, ii) blending of representations (see foot note Section 1.7.7) and, and iii) introducing equations as qualitative reasoning tools in comparative proportional reasoning (from here on referred to as qualitative reasoning) influence students' conceptual understanding of i) the concept of acceleration and ii) the conceptual relationships involving acceleration?

The first three iterations have several important implications that informed the development of this fourth iteration of my study. This chapter reports on this intervention, that took the form of a tutorial aimed to help students integrate the real world, the physics world and the mathematical world by using simple real world experiences to develop student ability with proportional reasoning using physical equations (design principles 1, 2, 3 and 4, p. 50). The methodology, sampling, data collection and analysis as well as the results of this iteration are presented in this chapter. The chapter concludes with a reflection on the intervention, discussion of the results, inferences made from the statistical evidence and the implications for teaching. Figure 7-1 is a representation of where this chapter fits in the broader DBR.

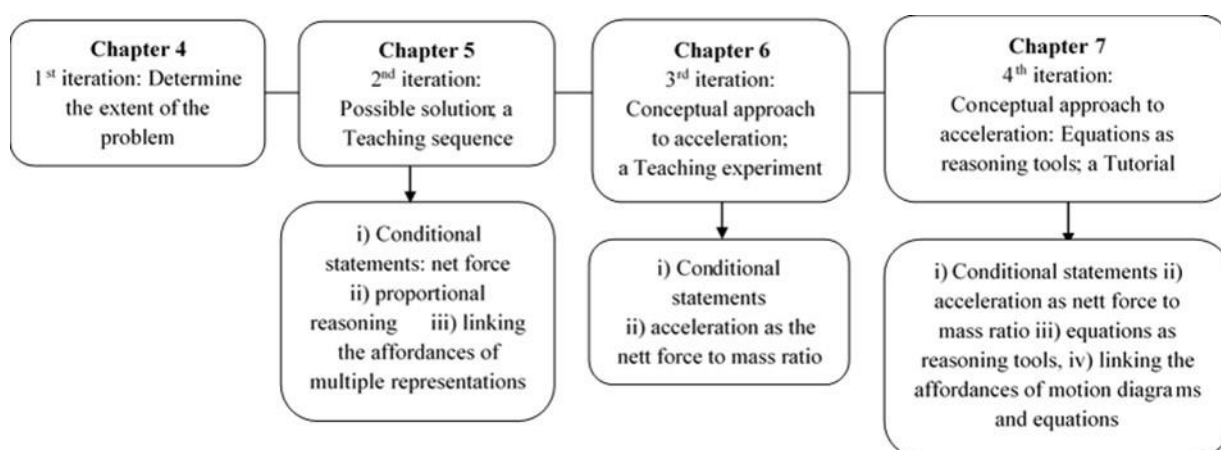


Figure 7-1: Representation of where the chapter fits in the DBR

7.2 Research design

The methodology for this iteration of the DBR followed an approach similar to a quantitative quasi-experimental research design. The iteration took the form of an intervention which consisted of a presentation/lecture followed by a session in which students had the opportunity to solve specific problems related to the topic of the presentation. The format of the intervention, a large group in a single room with a considerable number of teaching assistants present as well as the teacher, was the usual format for this class for these students. During the problem solving session the students were free to engage in discussions with or seek assistance from the lecturer, the teacher assistants or their fellow students. At South African universities classes that allow for problem solving sessions with informal engagement between students, teacher assistants and lecturers regardless of the number of students, are called tutorials. Due to the large number of students involved in first-year undergraduate physics at the institution in which this iteration was conducted, tutorials usually take place in the first-year laboratory that accommodates 300 students at a time, which is why the tutorial that formed this fourth iteration was implemented with a single intact group, as already suggested above and as further described below.

7.3 Methodology

The fourth iteration consisted of a teaching intervention in the form of a tutorial (described above in Section 7.2) intended to repeat and evaluate specific parts of previous iterations in the previous iterations. The iteration intended to i) explain the concept of conditional statements as used to simplify real world physics and address the hitherto missing conception of air resistance that had been shown in a previous iteration to need explicit tutoring (design principle 2, p. 50), ii) facilitate a better understanding of the concept of acceleration by focusing on a conceptual approach of “acceleration as the net force to mass ratio” approach (design principle 3, p. 50), and iii) advance

conceptual coherence by linking the affordances of physics equations and other multiple representations, as qualitative proportional reasoning tools (design principle 4, p. 50). Figure 7-2 presents the main features of the fourth iteration of the study.

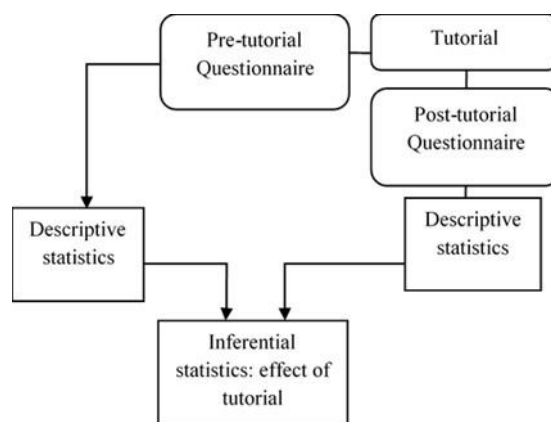


Figure 7-2: Main features of the fourth iteration

A pre-tutorial questionnaire (described in Section 7.3.3.1. below) served a dual purpose; to complete the quasi-longitudinal study that formed part of the first iteration, and to establish a point of reference with which to compare the student responses after receiving the tutorial. Comparison between individual student pre- and post-tutorial questions by using inferential statistics allowed me to draw conclusions on the influence of the effectiveness of the tutorial in meeting its aims.

7.3.1 Research participants

The study was conducted with first-year undergraduate physics students at a South African University. All first-year physics students (682 students) from both calculus-based (CB) and non-calculus based (NCB) groups completed the pre-tutorial questionnaire. However, due to the differences in their curricula, the calculus-based (CB) students did not participate in the tutorial or the post-test part of the study. As a result, only the students enrolled for non-calculus based (NCB) physics, (N= 297) participated in the tutorial and post-tutorial questionnaire. Table 7-1 presents the distribution of students who participated in the pre-test, tutorial and post-test parts of the study, in terms of gender and course enrolled.

Table 7-1: Distribution of students in terms of gender and study module

	N	% Female	% Male	% CB	% NCB
Pre-test questionnaire	682	39	61	59	41
Only Pre-test questionnaire	385	20	80	99	1
Tutorial and pre-post-tutorial questionnaire	297	64	36	7	93

The information presented in Table 7-1 indicates that 59% of all the students who completed the pre-test questionnaire, i.e. the first-year physics group, enrolled for CB physics while 7% of the students who participated in the tutorial and the pre-post questionnaire were enrolled in CB physics. There were more female than male students in the NCB group while the opposite is true for the CB group. Although this interesting information is not further investigated in this study it may be useful for gender-based research regarding introductory mechanics.

7.3.2 Method

The alternative teaching approach based on the net force to mass ratio (reported in Chapter 6) and qualitative proportional reasoning (reported in Chapter 5) were revised and reconsidered in the light of data from both previous iterations, and implemented with a different group of students in this iteration. Due to differences in the curriculum for the previous group and the group who participated here and with the focus in this iteration being on introducing qualitative reasoning, the practical component of the previous iteration was not repeated. The tutorial consisted of four parts, shown in Figure 7-3 and then described in detail in separate sub-sections.



Figure 7-3: The four parts of the tutorial

7.3.2.1 Part 1

Because the teaching of these undergraduates was done in a way which is usually described as a *tutorial* at South African universities, I use the term tutorial to describe the nature of tuition followed in the iteration reported in this chapter. In Part 1 of the tutorial I pointed out some difficulties posed by the traditional mathematical approach to teaching acceleration primarily to prepare the setting for the alternative approach. This involved discussing some of the results obtained in previous iterations of the research study. Student perceptions of equations as means of solving numeric problems and the limited use of contextual problems in the traditional mathematical approach to learning the topic were highlighted, as were the perceptions that physics concepts often only apply in special situations and that physics concepts were not applicable in students' daily lives. Figure 7- 4 presents a diagrammatic representation of the points that were discussed during the tutorial.

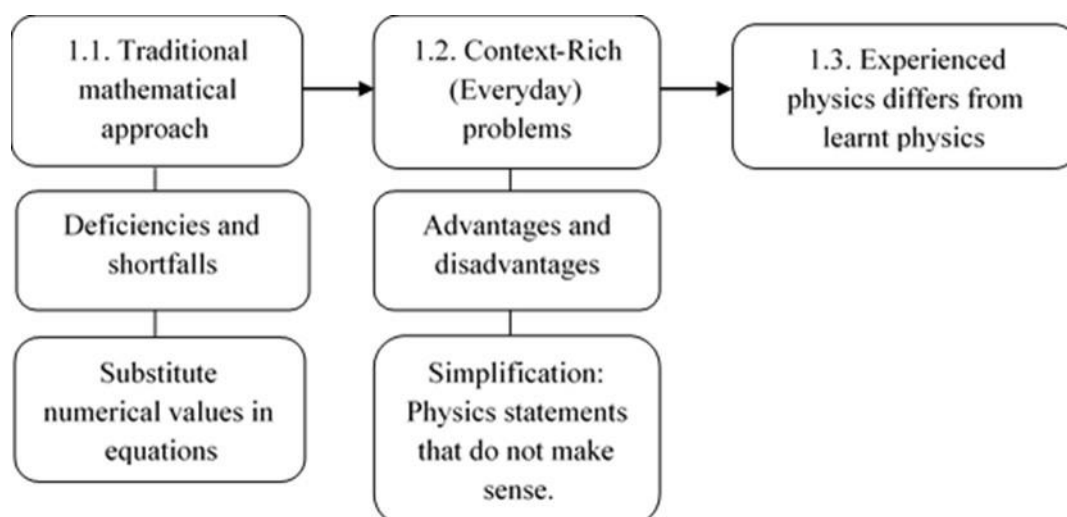


Figure 7-4: Points of discussion in current approach, and resulting difficulties

A more detailed version of the first part of the tutorial is provided as Appendix J: Traditional approach and resulting difficulties.

7.3.2.2 Part 2

Here I introduced a viewpoint about physics tools such as concepts, equations, physics symbols and quantities that was unfamiliar to many students. Figure 7-5 is a schematic representation of how the concept of physics tools was introduced.

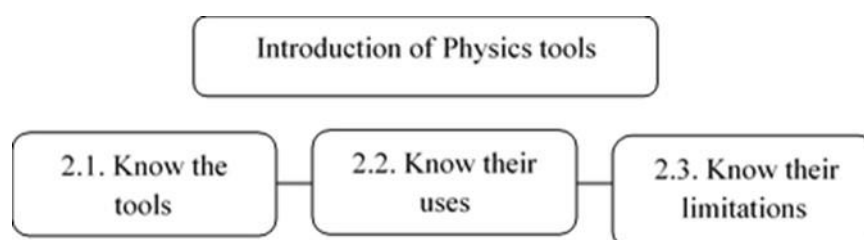


Figure 7-5: Implementing physics tools

The mistakes undergraduate students make in tests regarding the relationships between physics variables as represented in physics equations and the units of quantities reveal that their knowledge of how to use the “tools” of physics, e.g. concepts, laws, equations, physics symbols and quantities, is limited. As a result, a rich mine of information contained in equations, physics laws and definitions remains hidden from them.

For example, following the sequence described in Figure 7-5, I emphasized the difference between physics equations and similar mathematics equations, highlighting the complexity of physics equations and their meanings. For example, the similarity between the mathematical equation

$$y = mx + c \quad [\text{Eq. 1}]$$

and the physics kinematic equation

$$\mathbf{v}_f = \mathbf{v}_i + \mathbf{a}\Delta t \quad \text{rewritten as } \mathbf{v}_f = \mathbf{a}\Delta t + \mathbf{v}_i, \quad [\text{Eq. 2}]$$

lies in that both equations can be represented by linear graphs with y and $\mathbf{v}_f$ respectively as the dependent variables and x and Δt as the independent variables. If presented by graphs, c and $\mathbf{v}_i$ respectively indicate where the graphs intersect the vertical axis while m and $\mathbf{a}$ represent the gradients/slopes of the graphs. However, while the mathematical equation represents a generic equation for any one-dimensional linear graph, the physics equation represents a specific relationship between the physics quantities of initial velocity, final velocity, acceleration and the time interval.

A problem often overlooked by lecturers is the different meanings symbols have in pure mathematical and in physics equations. While the letter m represents the slope of a straight line graph in mathematics and is solely a number (always 'unitless'), in physics m represents the mass of an object and has a unit (usually kg). Although it is unlikely that students will interpret the meaning of the symbol c in

$$y = mx + c \quad (\text{Eq. 1})$$

in terms of the physics meaning of c as the speed of electromagnetic waves in vacuum, there is a higher probability that they may get confused with the difference in usage of the symbols of x and $\mathbf{a}$ in the mathematical equation

$$y = ax^2 + bx + c \quad [\text{Eq. 3}]$$

and the physics equation

$$\Delta \mathbf{x} = \mathbf{v}_i \Delta t + \frac{1}{2} \mathbf{a} \Delta t^2. \quad [\text{Eq. 4}]$$

During my more than thirty years of teaching experience I had witnessed only a few grade 12 students associating the mathematical equation representing a parabola (equation 3), with the physics equation representing the relationship between displacement and acceleration (equation 4). It seems that students do not see the similarities and differences between mathematical knowledge and physics knowledge. For example, confusion regarding the use of the symbol x in the two equations mentioned above, as the independent variable in equation 3 and as the displacement dependent on the acceleration in equation 4, was reported in an unpublished pilot study I did as a research project for my B.Ed. Honours study in 2013.

Almost all the laws of mechanics contain conditional statements identifiable by preceding words such as “if”, “when”, “as long as” etc., e.g. Newton 2: “*If a net force acts on an object the object accelerates...*”, the condition here being “a net force acts on an object”. When students understand the conditions of the various basic physics “tools”, e.g. concepts, units, laws, equations, etc., then it is more likely that they will use these resources in appropriate ways. For example, the kinematics equations (e.g. equations 2 and 4 above) only apply with constant acceleration, i.e. when a constant net force is applied to an object. All these resources are interconnected. The alternative approach to introducing acceleration as the net force to mass ratio results in considering the effect of the net force on the motion of an object – acceleration – and from there the ripple-effect on displacement and velocity in certain time intervals. Such an approach therefore also contributes to coherence amongst physics concepts.

7.3.2.3 Part 3

This part of the tutorial addressed the conditional statement “in the absence of air resistance” (lack of understanding of which is essentially a missing conception). The demonstration used in the previous iterations reported in Chapters 5, 6 and 7 was again used to introduce discussion on the effect of air resistance on different sets of objects of different mass. Figure 7-6 below is a diagrammatic representation of the steps followed in the demonstration and associated discussion.

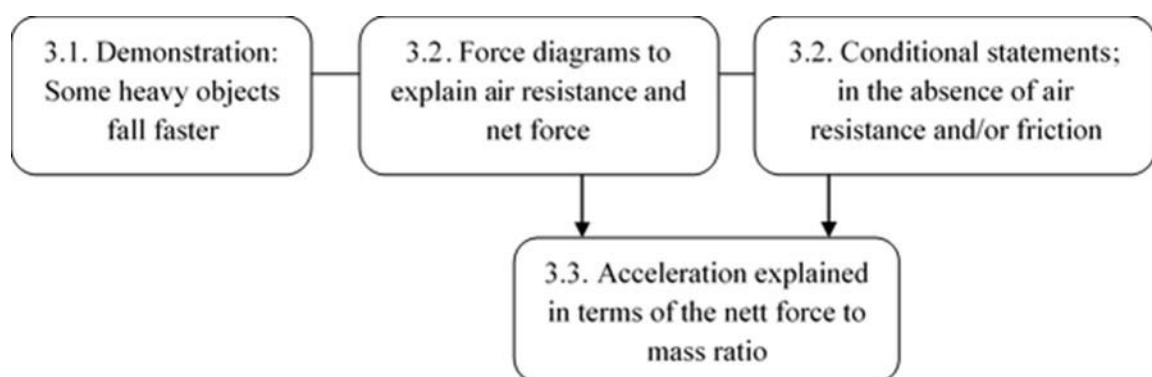


Figure 7-6: Steps followed in part 3 of the tutorial

The demonstration (step 3.1 in Figure 7-6) followed a POE protocol. A set of equal-sized but different mass balls (a steel ball and a polystyrene ball) were dropped from the same height, about 0,5 m. The students were asked to write their prediction of which ball would land first, then watch the demonstration and write their observation. Next the motion of two sets of paper holders used for making cupcakes, a single holder and a double holder, dropped from the same height was compared. In contrast to the two balls which landed so close to the same instant as to be indistinguishable to the eye, that is effectively together, the double cupcake holders fell noticeably

faster and landed before the lighter, single cupcake holder. Due to time restrictions the Explain part of the POE protocol could not be done by the students, but took the form of a short lecture on conditional statements (step 3.2. in Figure 7-6) and the effect of air resistance on objects with the same size but different masses. The influence of the resistive force was explained in terms of the net force to mass ratio, an explanation suggested to me by Gunstone (2016) (step 3.3 in Figure 7-6).

Force diagrams were again used to explain the effect of air resistance in the context of the sum of the forces on falling objects (step 3.4. Figure 7-6), a repetition of the explanation in the first iteration. A concise version of the explanation is included as Appendix K: Explanation of the effect of air resistance. The condition of 'the absence of air resistance' was added to emphasize the effect of this condition on the net force, and concept of acceleration as the net force to mass ratio on falling objects.

7.3.2.4 Part 4

The final step in the tutorial was to introduce qualitative reasoning by using equations as reasoning tools and blending multiple representations. Figure 7-7 shows the progression of this part of the tutorial.

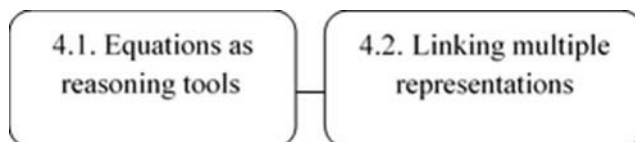


Figure 7-7: Progression of Part 4

In this part the motions of two objects were compared in questions set in a variety of contexts. For example, students had to consider the motion of two balls with different masses released from different heights simultaneously. The condition of the absence of air resistance had to be considered, which meant that the net force to mass ratio for each ball was taken to be the same, which in turn meant equal (gravitational) acceleration. The appropriate kinematics equation with which the motion could be described was used to compare the different physics quantities qualitatively as a proportionality. Multiple representations, e.g. pictorial, motion diagrams and equations, were blended and used to justify qualitative reasoning. A short version of Part 4 of the tutorial is included as Appendix L: Introduction to qualitative proportional reasoning; and Appendix M: Tutorial problems - qualitative proportional reasoning.

7.3.3 Research instruments

7.3.3.1 Pre-test

The influence of the tutorial with the alternative teaching approach on student conceptual understanding of acceleration was evaluated using their performance in conceptual pre- and post-tutorial tests - attached as Appendix I with post-test questions indicated in bold. The pre-test questionnaire was a version of the initial questionnaire used in the grounding of the DBR sequence (described in Chapter 5), altered to include more questions on motion along an inclined plane. It consisted of eight multiple choice items in which the motion of two objects had to be compared, and an additional question to evaluate student application of the net force to mass ratio after the tutorial. This additional question (question 9) was not included in the statistical analyses because it was not consistent with the other questions in terms of the physics variable to be determined.

7.3.3.2 Post-test

Four of the questions from the pre-test, including the question on the net force, were included in the semester test undertaken by the students; this served as a post-test. Not all the questions of the pre-test could be included in the post-test because the semester test involved more topics than the tutorial and so there was a limit on the number of questions that could be included.

7.3.4 Data analysis

Students with little conceptual understanding of free fall motion (i.e. in the absence of air resistance and friction) are more inclined to give an alternative conception as a response, for example that heavier objects will fall faster (Ferreira, Lemmer *et al.*, 2017). Answers pointing towards the alternative conception were therefore taken as an indication of a lack of understanding of acceleration as the net force to mass ratio. In analysing the results of the questionnaires, the change in choice from the alternative option (that heavier objects fall faster) to the correct option (assuming that the objects will have the same acceleration), is considered indicative of an increase in conceptual understanding. Previous research indicates that student understanding of the concept of gravitational acceleration is connected to the extent to which they associate an object's falling rate to its mass, especially if the object is projected vertically upwards or along an inclined plane (Ferreira, Lemmer *et al.*, 2017).

The pre-test responses of all students in the calculus- based (CB) and non-calculus-based (NC) modules were compared. Figure 7-8 shows how these data are presented here. Responses were

summarized in frequency tables (i.e. descriptive statistics) in terms of the correct answer and the “alternative choice”, namely that heavy objects fall faster.

The inferential statistics used to determine the influence of the conceptual approach to acceleration on student understanding of acceleration are describe in section 3.6.3. Figure 7-8 offers a summary of how the statistics were implemented in this iteration.

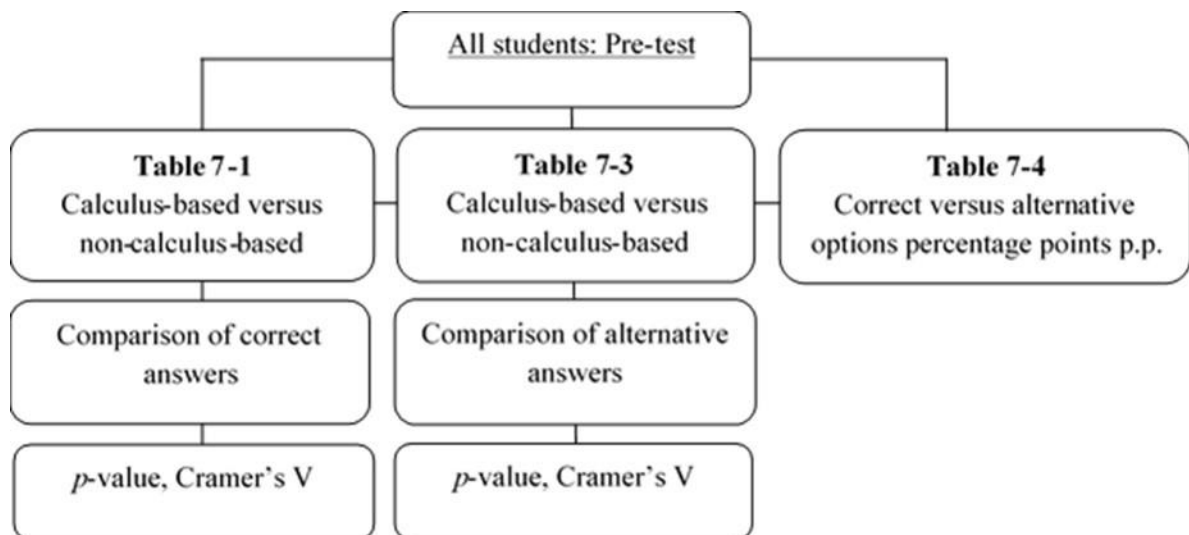


Figure 7-8: Summary of data analysis of pre-test results

The intent of this cycle of the research project was to obtain data with regard to the contribution of the tutorial to the enhancement of student conceptual understanding of acceleration. The post-test results were summarized in a frequency table and compared with the pre-test results using descriptive statistics. Figure 7-9 shows the approach to the data analysis of the pre-post-tutorial results.

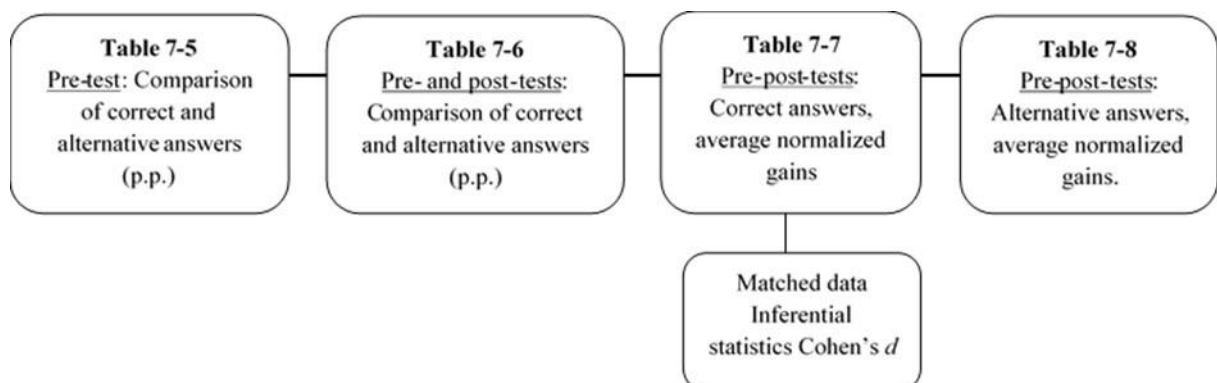


Figure 7-9: Summary of data analysis of pre-post tutorial results

Table 7-5 presents the comparison of the correct options for the pre-test responses and the alternative options. In Table 7-6 the same options were compared for the pre- and post-test

responses. The average normalised gain for the increase in correct answers was determined (Table 7-7) and the same formula was used to calculate the change in the choice of alternative option (Table 7-8). The average normalised gain, $\langle g \rangle$, is the degree of progress of the students and indicates the actual effectiveness of the tutorial. It is calculated as

$$\langle g \rangle = \left(\frac{\text{post-test score} - \text{pre-test score}}{100 - \text{pre-test score}} \right) \text{ (Hake, 1997).}$$

Two by two contingency tables of the pre-post-test results allowed calculation of Cohen's d (effect size) to allow inference about the practical significance of the gain/loss in responses pre-and post-tutorial. Effect size is a measure of how important a difference is (Ellis & Steyn, 2003). Because effect size accounts for the variance in individual scores, it is a more sensitive measure than the normalized gain. The main mathematical difference between normalized gain and effect size is that normalized gain does not account for the size of the class or the variation in students within the class, but effect size does seek to consider these variables. The inferential statistics for the questionnaire were calculated by using SPSS Statistics Version 22, Release 22.0.0.

7.4 Results

7.4.1 Reliability of research instrument

The reliability of the pre-test questionnaire was considered by determining Cronbach's Alpha. Cronbach's Alpha and the mean inter-item correlation were calculated to indicate the reliability of the research instrument. Inter-item correlations show the extent to which scores on one item are related to scores on all other items in a set of test items. The reliability, or internal consistency, of a measurement refers to the extent to which it measures a concept in a set of test items consistently. Cronbach's Alpha is a way of measuring the strength of that consistency. For this version of the questionnaire Cronbach's Alpha indicates good internal consistency of the items, calculated as 0.798. The mean inter-item correlation, 0.327, indicates that the items were homogeneous enough to consider accumulated scores as a single number, but with sufficient variance so as to show items were not isomorphic with each other.

7.4.2 Pre-test results: Calculus-based versus non-calculus-based groups

In this section the pre-test results of all students who participated in the pre-test are discussed. The students are considered in the two groups of differing enrolment: calculus-based (CB) or non-calculus-based (NCB) physics. This comparison was of interest because the requirements to enrol for the NCB physics module were less stringent than for the CB group which included, *inter alia*, all engineering students. For all the compared questions for the correct option, the p -values were less than 0.001. The comparison between the two groups' correct responses - objects in

free fall have the same acceleration regardless of their mass - is presented in Table 7-2 and between the alternative options of heavier objects fall faster in Table 7-3. The differences in the percentages of the two groups are reported as percentage points (abbreviated p.p.).

Table 7-2: Pre-test percentages, percentage point differences and Cramer's V of all students who chose the correct option

Correct option %	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
	F↓t	F↓v	C↙v	C↑t	C↓t	C↘t	C↑v	C↗d	F↓F
(CB)	91	80	25	46	82	49	48	39	51
(NCB)	52	38	9	15	41	22	24	23	45
CB-NCB p.p.	39	42	16	31	41	27	24	16	6
Cramer's V (ϕ_c)	0.433	0.426	0.212	0.326	0.417	0.277	0.251	0.174	0.053

Between 39 and 42 p.p. more of CB students answered questions 1, 2 and 5 correctly than the NCB group (row CB – NCB p.p.) - refer to Table 7-2. The difference is practically significant with ϕ_c between 0.433 and 0.417. All three of these questions were set in vertical downward motion. There was less difference between the answers for questions 4, 6 and 7, set in inclined downward or vertical upward motion (between 24 and 31 p.p., the ϕ_c values for these questions were 0.326 or less, not statistically significant). The smallest difference in the responses between the CB and NCB students was for questions 3, 8 and 9 - between 6 and 16 p.p. The practically insignificant differences in correct answers for questions 3 and 8, $\phi_c \leq 0.212$, indicate that low percentages of students in both CB and NCB groups gave the correct answer for motion along inclined planes. The small difference in the percentages points of students who had question 9 correct indicates that almost equal percentages of students from both groups gave a wrong answer regarding the magnitude of the force of gravity on objects of different mass.

Table 7-3: Pre-test percentages, percentage point differences, p-values and Cramer's V of all students who chose the alternative option

Alternative option %	Q1 F↓t	Q2 F↓v	Q3 C↙v	Q4 C↑t	Q5 C↓t	Q6 C↘t	Q7 C↑v	Q8 C↗d	Q9 F↓F
(CB)	9	18	37	25	10	36	46	49	41
(NCB)	42	52	51	27	42	41	59	57	37
CB-NCB p.p.	- 33	- 34	- 14	- 2	- 32	- 4	- 13	-8	4
p-value	<0.001	<0.001	<0.001	<0.607	<0.001	<0.318	<0.002	<0.055	<0.006
Cramer's V	0.388	0.347	0.135	0.019	0.364	0.038	0.116	0.072	0.155

Although the *p*-values indicate a statistically significant association between the CB and the NCB groups' answers for questions 4, 6, 7, 8 and 9, - refer to Table 7-3, - the differences are not practically significant, as indicated by Cramer's V. The difference of CB students choosing the alternative option to question 9 (indicating that the two falling objects experience equal forces) is higher than the NCB students who made the same choice.

In Table 7-4 below the percentages of student choices of correct versus alternative option are presented.

Table 7-4: Percentages of correct versus alternative option of heavier objects fall faster of all pre-test responses in percentage points

All students (%)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q7	Q9
Context	F↓t	F↓v	C↙v	C↑t	C↓t	C↘t	C↑v	C↗d	F↓F
Correct	74	62	18	33	64	37	37	32	48
Alternative	23	33	43	26	25	38	52	53	39
Difference (Correct – Alternative) p.p.	51	29	-25	7	39	-1	-15	-21	9

Questions 1, 2 and 5 were the only questions for which the context was vertical downwards motion and the physics variable to be solved was either time or velocity. For these, the correct response was chosen by between 29 p.p. and 51 p.p. more students than was the alternative option. For question 4 set in vertically upward context with time as the physics variable to be solved the correct response was chosen by less than 10 p.p. more students than was the alternative option. Only 9 p.p. more students answered in question 9 that the force of gravity on a heavier object

was more than on a lighter object. The context for questions 3, 6 and 8 was motion along inclined planes. For questions 3 and 8 where either velocity or displacement was the physics variable to be solved, the correct response was between 21 and 25 p.p. less students than the alternative option. For question 6 set in context of inclined downwards motion with time as the physics variable, the correct response was 1 p.p. less than the alternative response. The correct response for question 7 with context vertical upward motion with velocity as the physics variable to be solved, was 15 p.p. less than the alternative response.

7.4.3 Pre-post results of the non-calculus based group

The pre-test results of the non-calculus-based students who participated in the tutorial and both the pre- and post-tests are presented in Table 7-5.

Table 7-5: Difference between % NCB students who chose the correct versus the alternative option in pre-test

Test group: pre-test %	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
Context	F↓t	F↓v	C↙v	C↑t	C↓t	C↘t	C↑v	C↗d	F↓F
Correct	52	38	9	15	41	22	24	23	45
Alternative	42	52	51	27	42	41	59	57	37
Difference (Correct – Alternative) p.p.	10	-14	-42	-12	-1	-19	-35	-34	8

The results summarized in Table 7-5 show that for the questions concerning motion along inclined planes or vertical upward motion with either velocity or displacement as the physics variable to be solved, questions 3, 7 and 8, the correct response was between 34 to 42 p.p. less students than the alternative response. For questions 4 and 6 motion along an inclined plane or vertical upward motion with time as the variable to be solved, the corrects option was 12 to 19 p.p. less students than was the alternative response. Questions 1, 2 and 5 were all set in vertical downwards context. For question 1 and 5 where time was the physics variable to be solved the correct response was respectively between 10 p.p. students more and 1 p.p. students less than the alternative response. For question 2 where velocity was the physics variable to be solved, the correct response was given by 14 p.p. students less than was the alternative response. For question 9 where the force of gravity on objects of different mass had to be compared, 8 p.p. more students chose the correct response than did the alternative response.

The choices for the correct and the alternative options pre-and post-instruction are presented in Table 7-6.

Table 7-6: Comparison of % correct and alternative answers in pre-and post-tests

Correct %	Q3	Q5	Q6	Q9	Alternative %	Q3	Q5	Q6	Q9
	C↯v	C↓t	C↘t	F↓F		C↯v	C↓t	C↘t	F↓F
Pre-test	9	41	22	45	Pre-test	51	42	41	37
Post-test	29	68	74	70	Post-test	23	11	11	20
Difference (post – pre) p.p.	20	27	52	25	Difference (post – pre) p.p.	-28	-31	-30	-17

All four questions that were repeated in the post-test (questions 3, 5, 6 and 9) showed both an increase in the percentage of correct answers and a decline in the percentage of students who chose the alternative option, in comparison with pre-test mean scores. Figures 7-10 and 7-11 present these changes visually.

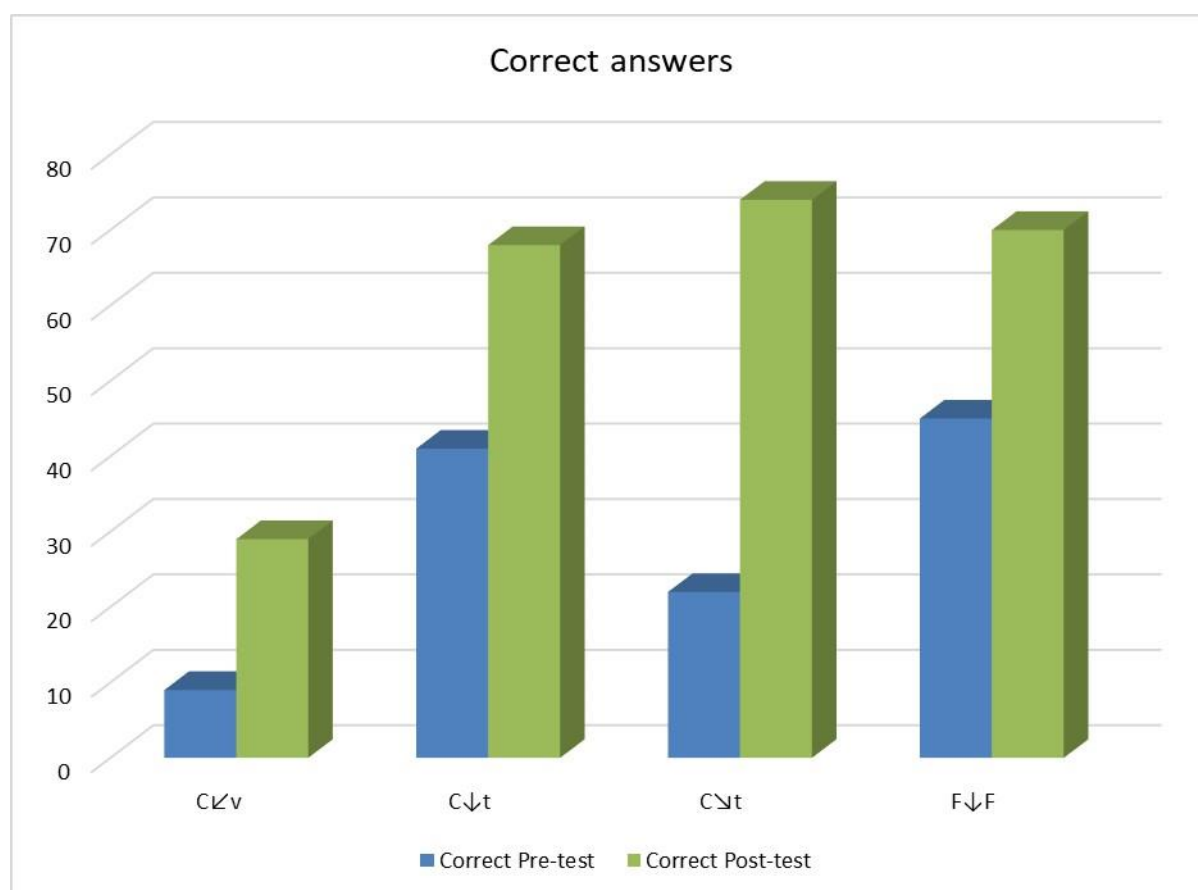


Figure 7-10: Graphical comparison of correct answers in pre-and post-tests

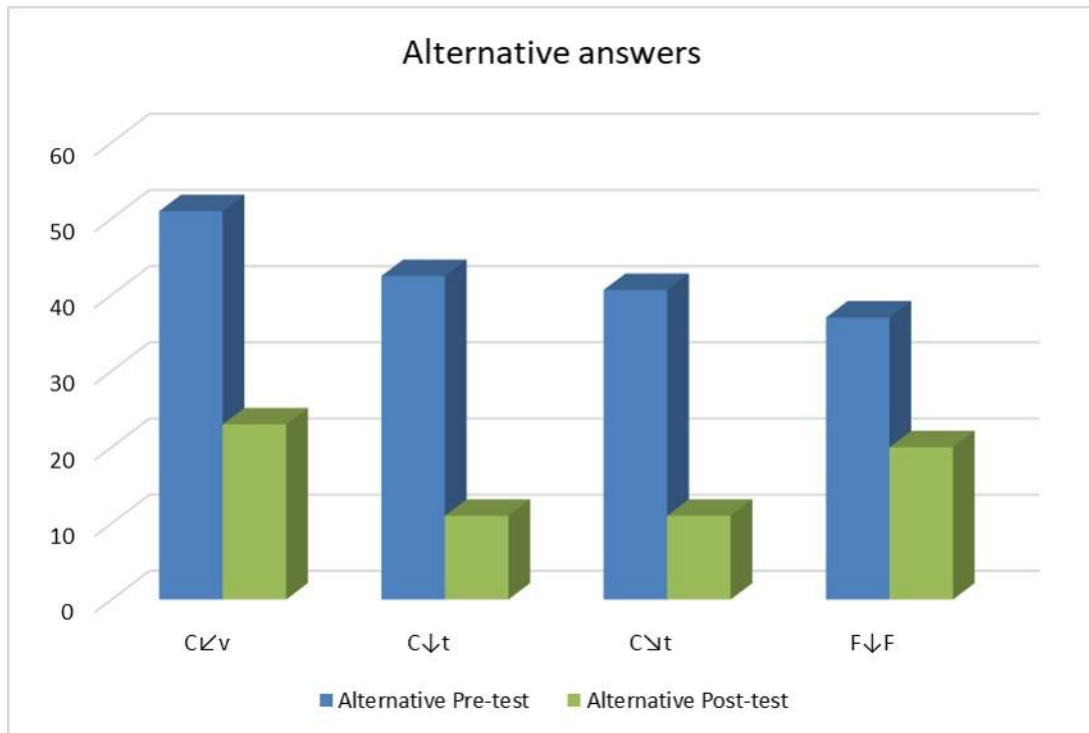


Figure 7-11: Graphical comparison of % choosing the alternative option in pre-and post-tests

In Table 7-7 the inferential statistics indicating the significance of the differences in the percentages of correct responses are presented.

Table 7-7: Inferential statistics: Normalized gain and Cohen's d effect size

Pre-post-test – Correct options								
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Question	Q3	Q9	Q5	Q10	Q6	Q11	Q9	Q12
Context	C↙v	C↙v	C↓t	C↓t	C↘t	C↘t	F↓F	F↓F
% correct	9	29	41	68	22	74	45	70
% Learning gain	20		28		52		26	
Normalized gain	0.2		0.5		0.7		0.5	
Cohen's d (d)	0.73		0.58		1.27		0.53	

The results indicate that the learning gain for all three questions concerning gravitational acceleration (questions 3, 5 and 6) in the post-test was practically significant, with effect sizes of $d = 0.73$ for question 3, $d = 0.58$ for question 5 and $d = 1.27$ for question 6 respectively. The

normalized learning gains for question 9 was 0.50, which is also practically significant as indicated by $d = 0.53$.

The inferential statistics concerning the decline in the alternative options, presented in Figure 7- 11, are presented in Table 7-8.

Table 7-8: Inferential statistics: Normalized decline and Cohen's d effect size for alternative options

Alternative option	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Question	Q3	Q9	Q5	Q10	Q6	Q11	Q9	Q12
Context	$C \nearrow V$	$C \nearrow V$	$C \downarrow t$	$C \downarrow t$	$C \nearrow t$	$C \nearrow t$	$F \downarrow F$	$F \downarrow F$
%	51	23	42	11	41	11	37	20
p.p. decline	28		31		30		17	
Normalized decline	-0.6		-0.5		-0.5		-0.3	
Cohen's d (d)	0.40		0.46		0.94		0.41	

The results indicate a 0.50 to 0.60 p.p. normalized decline in the choice of alternative options for the questions in the post-test concerning gravitational acceleration (refer to Table 7-8). The normalized decline in the conception that falling objects experience equal force was 0.3 p.p. For questions 3, 5 and 9 the decline in the choice of alternative options post-instruction is of medium practical significance as shown by the effect sizes between 0.40 and 0.46. The effect size of $d = 0.94$ for question 6 is of high practical significance. The decline in the answers that indicate the presence of alternative conceptions after the tutorial (Table 7-8), is also presented visually as a graph (Figure 7-11).

7.5 Discussion of results

7.5.1 Calculus-based and non-calculus-based student pre-test responses

Although the calculus-based students performed better in the pre-test than the non-calculus-based students (see Table 7-2), their performance in the questions with motion along an inclined plane and in the upward direction showed that they experienced the same difficulties as the non-calculus-based students. This is noteworthy because students enrolled for the calculus-based physics module are typically either engineering students or students who intend to major in Physics. Both these courses have higher requirements for admittance, which means it is most probable that students enrolled for the calculus-based module performed better in the grade 12 exams for Physical Sciences than the students enrolled for the non-calculus-based module.

The high percentage of correct answers for questions 1, 2 and 5 (see Table 7-2) may appear to indicate that the students know and understand the concept of free fall, i.e. equal acceleration for objects falling in the absence of air resistance. However, the dramatic decline in correct responses for questions posed in non-traditional settings indicates that even the CB students struggle to apply the concept - or the consequences - of free fall in unfamiliar circumstances. For questions 1, 2 and 5 the correct answer that objects of different mass released simultaneously from the same height will reach the ground at the same time/with the same speed does not necessarily require conceptual understanding and can be produced by rote learning. A lack of conceptual understanding is illustrated by the relatively low percentages of correct answers to questions 3, 4, and 6 to 8. The Cramer's V values for these questions also show that the trend of the responses is the same for both CB and NCB students.

The result of question 9 was most unexpected as 51% of the CB group and 45% of the NCB group chose the answer indicating that the (gravitational) forces acting on the falling objects were equal in magnitude. That is, about half of both groups did not comprehend the concept of acceleration as the effect of the net force acting on an object, i.e. the net force to mass ratio.

7.5.2 Discussion of test group pre-post-test results

All the post-test responses had a normalized gain in correct responses between 0.2 and 0.7, and there was a practically significant decline in the choice of the alternative option that heavier objects fall faster, which strongly suggests that the alternative conceptual approach to acceleration as the net force to mass ratio may have contributed to the students improved performance in the post-test.

The results in Table 7-6 indicate an increase in the correct answers of the NCB group on the post-test, a result which can be ascribed to the tutorial because of the very specific nature of the questions and the improvements. The graph depicted in Figure 7-10 shows that for question 6 motion along an inclined plane where time was the physics variable asked the increase in correct answers was the greatest. The graph representing the alternative options in the post-test (Figure 7-11) indicates the lowest post-instruction percentage for the same question, and the inferential statistics suggest that the decline is of high practical significance, $d = 0.94$. The low increase in the correct answers for question 3 (C✓V) may indicate that, despite a better understanding of the concept of acceleration, students were still struggling to relate acceleration to velocity, or to any kinematics variable other than time. This indicates that student difficulties with understanding the velocity-displacement-time relationships with acceleration in different directions of motion (upwards, downwards and at an angle) were not diminished by the net force to mass approach. This issue needs to be investigated in further research stemming from the study.

7.6 Conclusion

The influence of the alternative teaching approach on student conceptual understanding of gravitational acceleration was evaluated using their performance in pre- and post-conceptual tests. In accordance with the research question (and with design principles 2, 3 and 4, p. 50) the conceptual approach to acceleration entailed i) an alternative representation of acceleration as the net force to mass ratio, ii) a blending of representations, and iii) introducing equations and the affordances of multiple representations as qualitative reasoning tools, and then considering the influence on student conceptual understanding of i) the concept of acceleration, and ii) the kinematic relationships resulting from it.

The evidence obtained in this iteration indicates that the tutorial on the conceptual approach to acceleration as the net force to mass ratio had a practically significant effect in enhancing the student conceptual understanding on the concept of the acceleration of an object, with average normalized gains in understanding as represented by pre- and post-test data of between 0.20 and 0.70 in correct answers. This evidence links to the results obtained in previous iterations of the research study that explaining conditional statements and clarifying the consequences of such statements contribute to increased student conceptual understanding (design principle 2, p. 50).

The results indicate that presenting acceleration as the net force to mass ratio contributes to both student conceptual understanding of acceleration and their ability to reason qualitatively on problems concerning accelerated motion (design principle 4, p. 50). The evidence suggests that an approach to enhance understanding of the concept of acceleration and its related concepts, based on students' everyday experience and containing some core concepts, may be helpful to enhance student understanding of conceptual relationships. On the basis of this evidence an argument for reconsideration of the current instructional practice of presenting acceleration as the time derivative of velocity is presented.

Based on the statistical evidence of the practical significant influence of the tutorial, it is reasonable to predict that the level of performance of the CB group (who did not participate in the tutorial) would show similar gains if the tutorial was presented to them, particularly if we consider the similarities between the trends of the pre-test responses of the CB and the NCB groups (see Table 7-3). An additional consequence of presenting this tutorial to CB students may be that the gain in conceptual understanding could not only benefit students for the duration of their introductory physics year but may also provide constructive scaffolding for the consecutive years of their study in physics (design principle 1, p. 50).

The results of this fourth iteration also indicated that student difficulties with implementing the kinematic (velocity-displacement-time) relationships with acceleration along inclined planes seem not to be diminished substantially by the net force to mass approach. In an attempt to address this deficit, further research on qualitative conceptual reasoning is being undertaken in collaboration with two other universities in South Africa; this further research is not part of this thesis study and so is not reported here.

7.7 Research resulting from the study

The impact that explaining simplification and the conditional statement of ignoring the effect of air resistance had on student developing conceptual understanding on the concept of acceleration informed the fifth and last iteration of this study. In this further investigation of this issue it was logical to attempt an investigation into the conditions under which the effect of air resistance might reasonably be ignored. The outcome of this further investigation was the development of a set of graphs which illustrate and explain the actual effect of air resistance on falling spherical objects and that show visually the detail of motion in the presence of air resistance and in the absence of air resistance. This then provides evidence to use in making judgements as to whether or not one can reasonably 'ignore air resistance', i.e. under what conditions falling objects can be considered to be in free fall. In the next chapter, Chapter 8, this fifth and final iteration of the DBR is presented.

CHAPTER 8: SIMPLIFICATION - WHEN IT IS REASONABLE TO IGNORE THE EFFECT OF AIR RESISTANCE

8.1. Introduction

This chapter reports on the fifth and final iteration of this DBR. The simplification of motion under gravity and explanation of the concept of free fall has been a major focus in the DBR, as can be inferred from Figure 8- 1. This chapter describes the development of representations that offer a more detailed understanding of the conditions under which the simplifying assumption, in the absence of air resistance, might be judged to be reasonable and justified. Figure 8-1 below gives a summary of the whole DBR and sets this fifth iteration in the complete cycle of iterations.

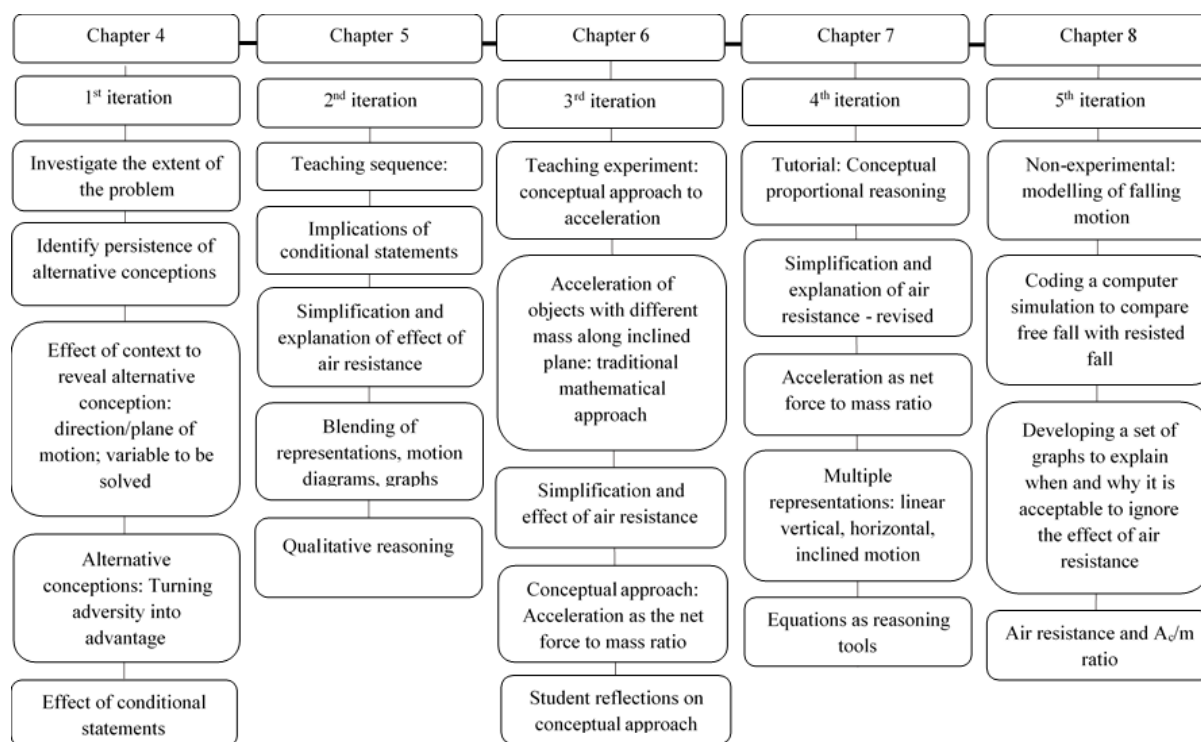


Figure 8-1: Placing Iteration 5 within the complete DBR

In alignment with the unique design principle for iteration 5, (refer to section 3.4), this chapter details the process of developing a graphical representation regarding the effect of air resistance, that is easy to present and understand. Here I describe the need for developing simple but relevant representations, what initiated the development of the representations that were the eventual product of this development, the process of development and the product of this iteration. An article describing the results of this iteration has been published, and is reproduced in Section 8.7 of the chapter. In this chapter I also include more detail regarding the background of approaches to idealizing everyday situations to model them as theoretical physics situations,

information regarding the progression of the investigation, and some further results (graphs) that are not included in the published paper.

8.2. Background and research question

If we want to understand the physics of the natural world (design principle 2, p. 50), we have to model it into physics understanding and knowledge. Real world phenomena are very complex to describe, explain and predict because they are influenced by a great number of variables (Duit *et al.*, 2014; Champagne *et al.*, 1982). Consequently, models are often used to facilitate understanding of a phenomenon. A model represents a phenomenon in terms of the similarities between the phenomenon and the model for which all kinds of idealisations and simplifications are made (Giere & French, 1989). An important kind of model often used in introductory mechanics is the one of idealisation; a deliberate simplification of something complex in order to make it more tractable (McMullin, 1970). Galilean idealisations are ones that involve purposeful distortion of certain relevant properties with the aim of removing the need to use complex and advanced physics and mathematics, and to therefore be able to focus on fundamental conceptual factors that are considered relevant to the effect under investigation (McMullin, 1985).

In the modelling step from the real world to the theoretical physics modelling of that reality we need to disregard certain aspects, very commonly for instance in introductory mechanics, air resistance or friction. The problem is, however, that students are not given any guidance as to how to decide what to disregard and what not, and what are the consequences of disregarding these aspects (Lubben, 2017). Students just must depend on either being told “forget about air resistance” or, in the absence of this instruction either rely on “we always disregard air resistance so we never bother about it” or assume that the problem/situation is a rare one where air resistance is to be considered. (Overwhelmingly students adopt the first of these [“always disregard air resistance”] because almost always this is what the teacher desires.) Consequently, it is extremely common for students to believe that physics and everyday knowledge have separate spheres of application. This in turn hinders the development of student perception of physics as a coherent body of knowledge (Muis & Gierus, 2014; Von Aufschnaiter & Rogge, 2015) that correlates with design principle 4, p. 50.

The results of the preceding iterations in the present study made it clear that it is useful to help students understand what the ‘condition of free fall’ means and what the consequences are when the motion of falling objects is idealized, i.e. when air resistance on falling bodies is ignored. The problem is how this idealisation can be understood and justified, and how the results obtained in this idealized model are relevant for everyday situations. The question that emerged as a consequence of the recurrent explanation of neglecting the effect of air resistance in every

preceding iteration of the DBR, and that guided the investigation that is the core of this fifth iteration was: what are the circumstances under which it is realistic to ignore the effect of air resistance on falling bodies?

8.3. Simplification revisited

Commonly, the instruction to disregard the presence of air resistance disconnects what students are learning from what they experience. In introductory physics ignoring the effect of air resistance is crucial however, since only this renders the mathematics involved in solving such problems tractable. The influence of conditional statements on student interpretation of physics problems and the confusion caused because of these, was identified in the reviews of literature in this thesis as a major obstacle for student development of conceptual understanding in the domain of introductory mechanics (refer to Section 2.6.2). Explanation of the conditional statement “in the absence of air resistance” has increasingly been an integral part of each one of the iterations of the research cycle, as is shown in Figure 8-2.

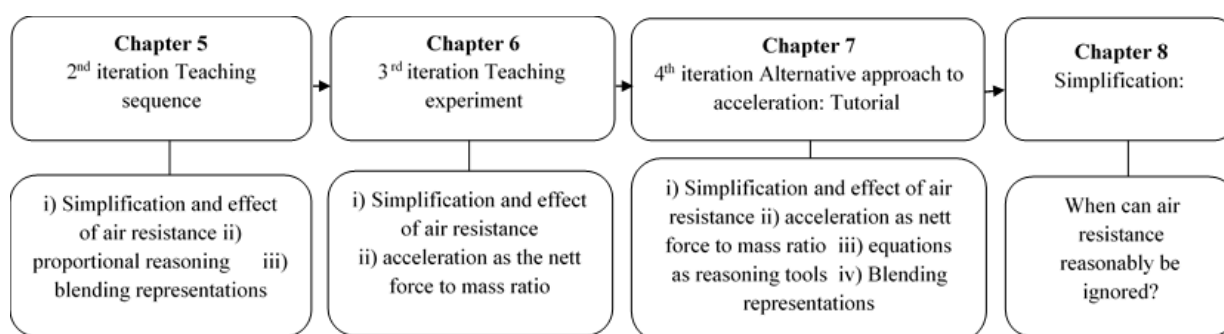


Figure 8-2: Recurrence of explaining the effect of air resistance in preceding iterations

The conditions under which it would be justified to ignore the effect of air resistance however are seldom mentioned or explained, let alone helpfully illustrated so that a judgement can be made as to whether or not ignoring is reasonable. The demonstration I used to introduce the unpredictable effect of air resistance, and to seek to create cognitive dissonance from the observations, was the one done in Iterations 2, 3 and 4 with i) two balls of different mass and ii) two sets of paper cups (used for baking cupcakes), one a single and the other a double paper cup. In both cases the objects were of the same size but different masses. In the case of the two balls, the mass of the steel ball was more than 250 times the mass of the polystyrene ball, while the mass of the double paper cup was twice that of the single paper cup. When each pair was dropped from a height of about 0,50 m, the two balls were observed to land at the same time but the single paper cup took notably longer to fall through the height than the double paper cup. The height from which the objects are dropped should be quite low to obtain the required effect, i.e.

to prevent the effect of air resistance to be noticed on the lighter ball. This observation provided an excellent opportunity to introduce and discuss the effect of air resistance on different objects and link it to terminal velocity. Figure 8-3 represents the logical argument that initiated this final part of the study.

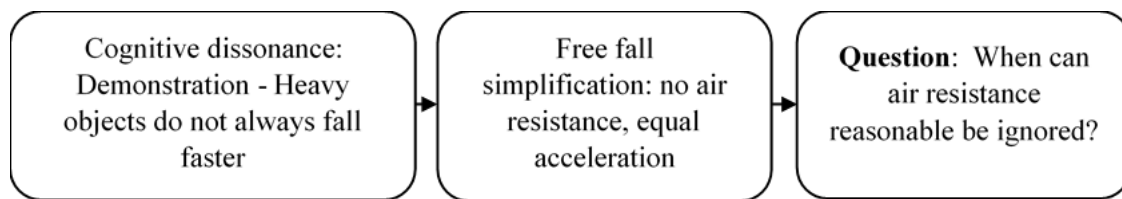


Figure 8-3: Diagram representing the argument leading to the final iteration

8.4. The progression of investigation and development of graphs

Besides the fact that the explanation on the effect of air resistance on falling objects in each of the iterations is very time consuming, it is not practical to execute demonstrations with a sufficient variety of objects and heights from which these fall as to allow inference on the conditions under which the objects would have sufficiently comparable accelerations as to be judged the same. A thorough review of the existing body of literature did not reveal information that could be used in simple explanations and comparisons of the effect of air resistance on various objects.

An existing graph evaluating how significant relativistic gravity is for a given astrophysical system (Hartle, 2003:5) inspired the development of a similar set of graphs for my situation. A Glowscript program that allowed visual comparison of the motion of a falling object in the presence and absence of air resistance (Alain, 2015) initiated the development of a code by which the motion (and properties) of a variety of falling objects and heights of falling could be modelled and compared. A colleague in the School for Space Physics at North-West University was most helpful in developing a computer code to model the motion of falling objects. To accomplish this, the equation of motion for a ball falling under the effects of both gravity and air resistance was solved numerically. This solution was then used to write a computer code simulating the motion for various real world balls, with their cross-sectional area to mass ratio ($\frac{A_c}{m}$) as the determining factor, and comparing the motion with free-fall. By modelling the deviation in falling height due to air resistance, we obtained data that allowed us to compile graphs from which the critical conditions for which air resistance reasonably can/cannot be ignored can be judged. Figure 8.4 shows the progression of the modelling process.

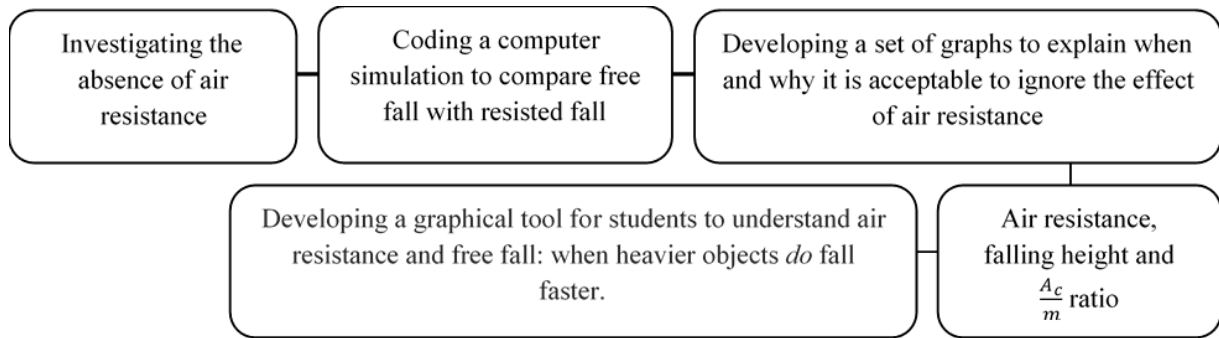


Figure 8-4: Progression of the modelling process

The coding and the physics involved in the development of the set of graphs are described in detail in Ferreira, Seyffert and Lemmer (2017), reproduced in Section 8.7. The motions of ten different sports balls, each with different mass and diameter, were modelled using the iPython code. The mass and diameters as well as the cross-sectional area to mass ratio ($\frac{A_c}{m}$) of the balls are presented in Table 8-1.

Table 8-1: Mass and diameters of the modelled falling balls

Ball	mass (kg)	mass (g)	diameter (cm)	$(\frac{A_c}{m})$ ratio ($\frac{cm^2}{kg}$)
table tennis	0.0027	2.7	4.00	0.4654
polystyrene	0.0000973	0.973	5.00	2.018
Metal ball	0.3698	369.8	5.00	0.005
tennis	0.0594	59.400	6.86	0.0622
baseball	0.1490	149	7.60	0.0304
cricket	0.1630	163	7.29	0.0256
soccer	0.4450	445	22.30	0.0878
basket	0.6237	623.7	23.88	0.0718
bowling	7.2600	7260	21.88	0.0052
shot put	7.2600	7260	13.00	0.0018

From the data generated by modelling the motion of the sports balls, a set of graphs was developed which related the effect of air resistance, the height of fall and the cross-sectional area to mass ratios ($\frac{A_c}{m}$) of the various balls. The set of graphs which resulted from this section of the DBR study is intended to compare the effect of air resistance on the motion of a number of falling

objects visually and also indicate when the effect of air resistance on the different balls could reasonably be ignored.

8.5. Graphs and interpretation of graphs

The following two graphs (Figures 8-5 and 8-6) are included in Ferreira, Seyffert *et al.*, (2017) in Section 8.7. In the first graph (Figure 8-5) the trajectories of the different balls in reality (i.e. with the friction of air resistance considered) compared to the trajectory of an object in free fall with no air resistance considered (i.e. frictionless), are shown.

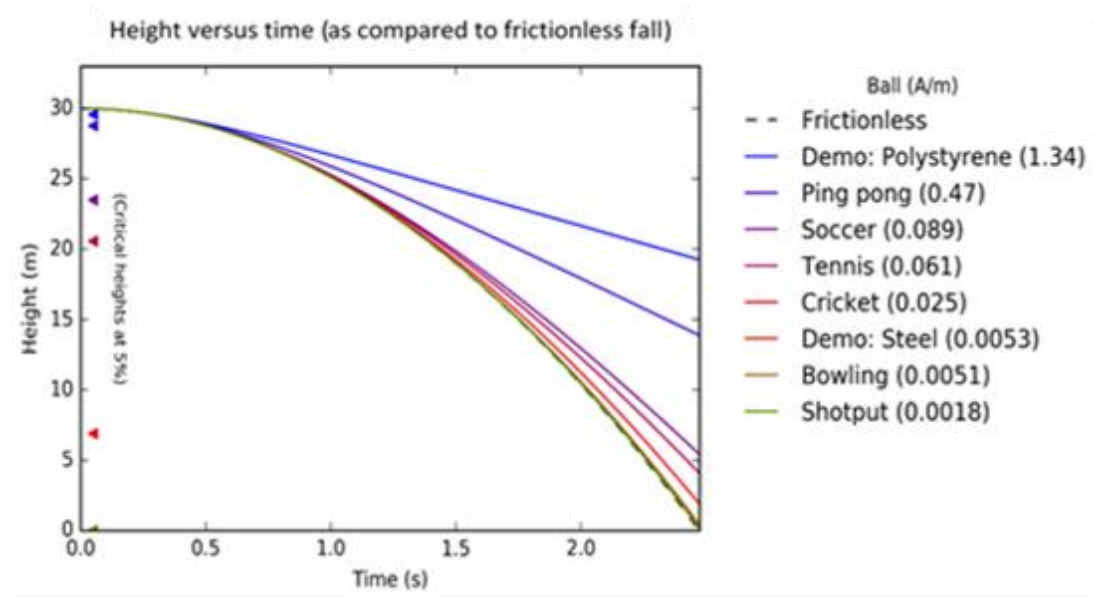


Figure 8-5: Time of fall with friction as compared to frictionless fall

The second graph (Figure 8-6) contained diagonal lines representing different heights, for which the slopes represented the critical cross-sectional area (A_c) to mass (m) ratio for objects falling from that specific height that result in air resistance having an observable effect on that object. A tolerance factor of 5% in the falling distance due to the effect of air resistance was chosen as the benchmark for observation of the effect of air resistance.

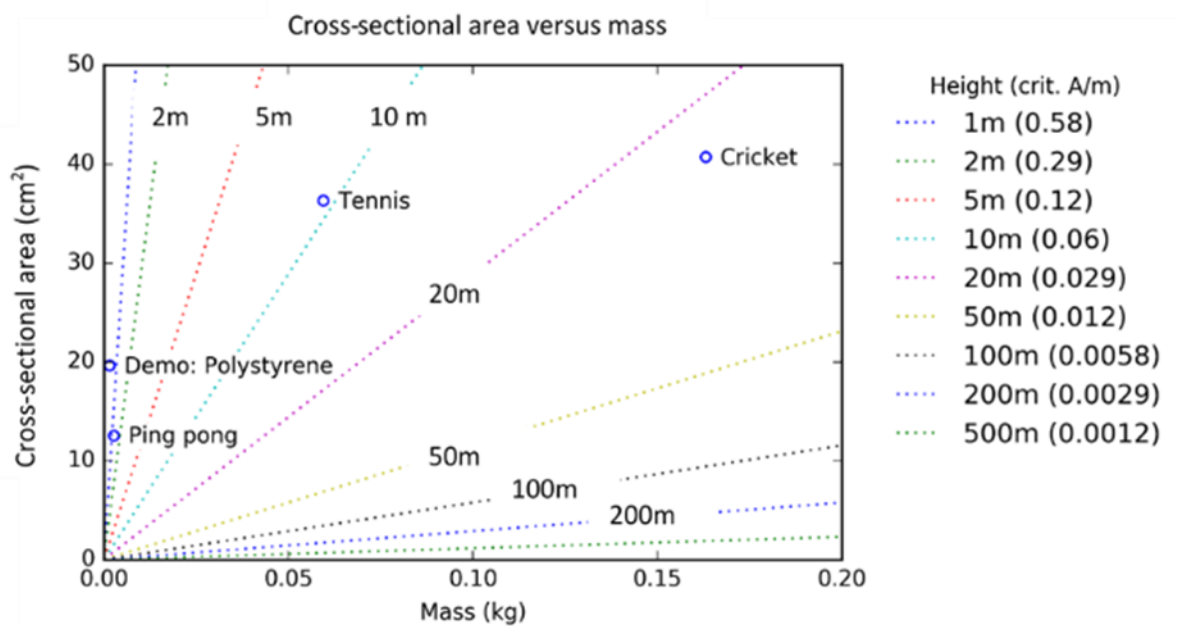


Figure 8-6: Relationship between $\left(\frac{A_c}{m}\right)$ ratios and height of fall

The graphs were intended as simple visual tools to indicate when, depending on the size (cross-sectional area), mass and falling height of individual balls, the effect of air resistance could reasonably be ignored and the motion could be considered as free fall. From the graphs it is clear that the effect of air resistance for balls with the smallest $\left(\frac{A_c}{m}\right)$ ratios, is the lowest. By comparing the $\left(\frac{A_c}{m}\right)$ ratios of the balls to that of the critical $\left(\frac{A_c}{m}\right)$ ratios for the different heights, it is easy to infer whether the effect of air resistance will be notable on a specific ball released from a specific height. Other contra-intuitive inferences can also be made. For example, the critical $\left(\frac{A_c}{m}\right)$ ratio for a height of 100 m is calculated as 0.0058 and the $\left(\frac{A_c}{m}\right)$ ratios for a steel ball and a bowling ball 0.0053 and 0.0051 respectively. This means that for a height of fall of 100 m neither one of the two balls' motion will show a 5% deviation due to air resistance, therefore, if this is judged to be an acceptable level of simplification for the circumstances of the problem/situation they can both be considered to be in free fall and will land on the ground at the same time.

In addition to the graphs published in the paper, supplementary graphs were developed that could be of interest to the non-novice physics student. Figure 8-7 below shows the fractional deviation due to air resistance in the displacement of the falling balls (using the point of release as reference). The horizontal dotted line indicates the 5% deviation line while the two vertical lines represent heights of 1 m and 10 m respectively. The graph can best be explained by an example. For instance, the actual motion of a soccer ball, represented by the dark green line, will deviate

by 5% from its free fall trajectory after it has fallen for approximately 6 m (shown by this being the point where the green line intersects with the 5% deviation line).

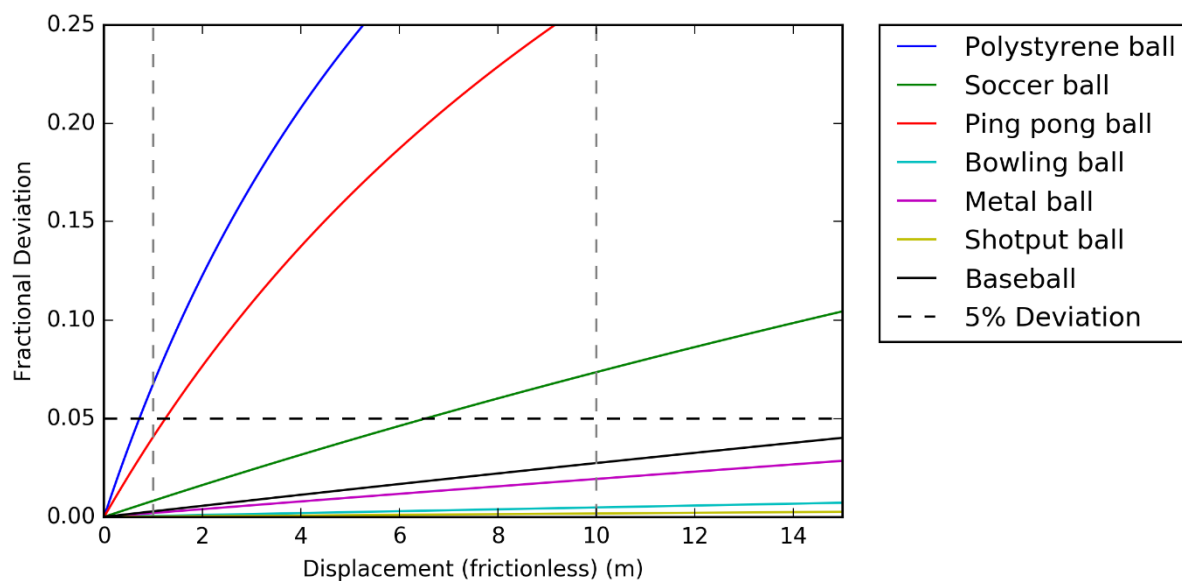


Figure 8-7: Relationship between fractional deviation and displacement

Figure 8-8 below represents the relationship between the same physical properties as Figure 8- 6 but on a logarithmic scale. Students knowing logarithmic scales may find it easier to understand that the positioning of balls to the left of a line in Figure 8-8 implies that the influence of air resistance is 5% or more for a ball dropped from the height represented by that line. For balls positioned to the right of a line it means that a 5% deviation will not be reached when dropped from that specific height. The logarithmic scale however, makes it difficult to determine the slope of the line, therefore Figure 8-8 was not included in the paper.

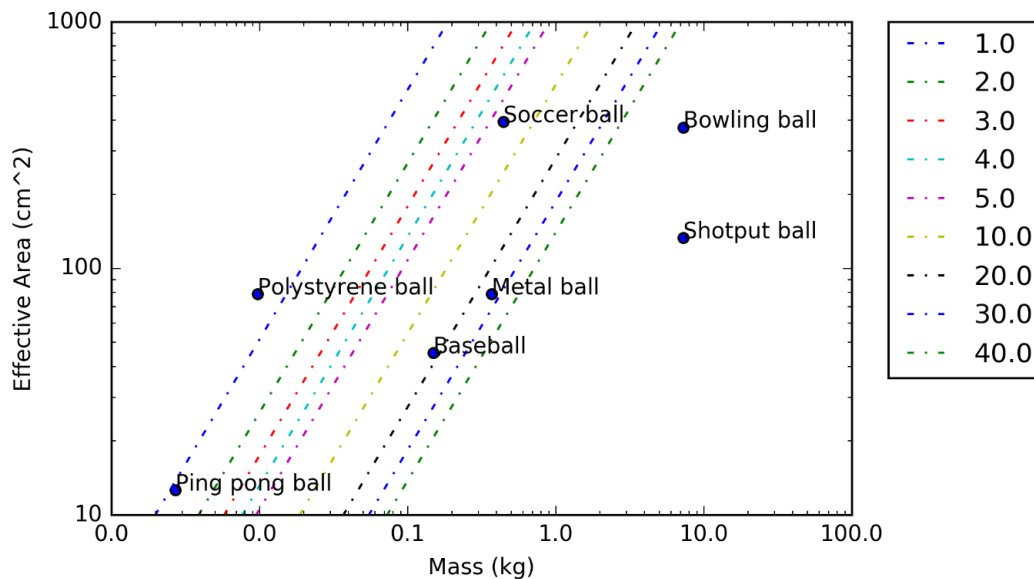


Figure 8-8: Logarithmic relationship between fractional deviation and displacement

By plotting the cross-sectional area and mass of a ball, the height from which the effect of air resistance will eventually be observed can be determined. The practical and educational implications of this section of the DBR study are described in Ferreira, Seyffert *et al.* (2017) (Section 8.7).

8.6. Conclusion

In this chapter the development of a set of graphs that are useful in explaining the physical conditions in which it is realistic to decide to ignore the effect of air resistance is described. Identifying such conditions not only validates the realistic use of conditional statements such as “in the absence of air resistance” but also contributes to the development of student views of physics as a collection of coherent concepts that is applicable in their daily lives (design principles 2 and 4, p. 50).

In the next chapter I present the conclusions of the study and highlight the outcomes of the DBR, its practical use and contribution to the existing body of knowledge in the field of physics education research.

8.7. Article published in Physics Education

Developing a graphical tool for students to understand air resistance and free fall: when heavier objects *do* fall faster

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Developing a graphical tool for students to understand air resistance and free fall: when heavier objects *do* fall faster

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Abstract

Many students find it difficult to apply certain physics concepts to their daily lives. This is especially true when they perceive a principle taught in physics class as being in conflict with their experience. An important instance of this occurs when students are instructed to ignore the effect of air resistance when solving kinematics problems. To a student, this assumption disconnects from their everyday experience. Mathematically, ignoring the effect of air resistance is crucial, however, since it renders such problems tractable. However, this step is rarely, if ever, provided with justification in undergraduate texts, leading students to believe that what they are taught does not apply to their everyday experience. Taking the additional step of clarifying when it is reasonable to ignore air resistance makes students' reconciliation of their everyday experiences with the physics principle of free fall more likely. In this paper we develop a graphical tool intended to make this step as simple and effective as possible. We do this by summarising the results of a set of numerical simulations of various balls falling under the effects of both gravity and air resistance by means of a carefully chosen graph: a plot of an object's cross-sectional surface area versus its mass. We further use our numerical results to evaluate how these two variables relate to the effects of air resistance for balls dropped from varying heights.

1. Introduction

A number of studies have shown that students often have pre-instructional conceptions and ideas about a number of physical phenomena that are not in harmony with what they are taught in physics courses [1, 2]. These existing beliefs are often resistant to change, and influence the understanding students develop during their science

tuition [3]. For example, when students are first taught about inertial motion, their experience that objects stop moving when one stops pushing them, conflicts with what they are taught (Newton's laws of motion). This conflict sometimes causes students to, for instance, subtly modify Newton's first law within their understanding to state that 'An object stays at rest unless a force acts on it,'

omitting the offending concept that an object in motion will stay in motion unless a force acts on it. This subtle modification, while more easily reconciled with their experience, effectively negates their tuition since they still do not understand Newton's first law.

While a variety of alternative conceptions exist, including the example above, those relating to gravity and the Galilean principle of free fall are of particular interest. A good understanding of these two concepts is critical in founding students' knowledge regarding a host of other physics concepts, including, but not limited to, Newton's Laws, the laws of conservation of energy and momentum, and projectile motion. In this paper we focus on one such alternative conception, specifically relating to free-fall motion, that 'heavier objects fall faster'. This conception is, of course, in conflict with the Galilean principle of free fall, and hinders students in their attempts to solve problems where a physics conception of free fall is crucial.

In the majority of undergraduate physics textbooks, the physics of falling objects is primarily discussed in terms of the Galilean principle of free fall, ignoring the effects of air resistance. While these texts do touch on the effects of air resistance, they typically limit their discussion thereof to a brief explanation of the concept of terminal speed [4, 5]. A predictable consequence of this focus on pure free fall in undergraduate tuition is that the majority of mechanics problems students are asked to solve are accompanied by statements like '...ignoring air resistance.' Physics problems accompanied by such statements, however, rarely serve their intended purpose of aiding the student in developing an accurate conception of Newtonian mechanics. Sanborn *et al* [6] reported that accurate conceptions of Newtonian mechanics only develop within physics problems that match students' terrestrial experience. Since air resistance plays a significant role in many phenomena students encounter in their daily lives, statements like '...ignoring air resistance' serve only to disconnect what they are being taught from their everyday experience.

These qualifying statements are not unwarranted, though, since they greatly simplify the mathematics involved in introductory mechanics problems by eliminating the variables associated with the effects of air resistance [7, 8]. For many learners, however, this seemingly unjustified

simplification calls into question the applicability of what they are taught. As a result, students doubt the integrity of physics as a coherent system of concepts to accurately describe and predict real-world phenomena [6].

This paper aims to reconcile students' everyday experience of falling objects with the Galilean principle of free fall. To do this we investigate the circumstances under which air resistance can justifiably be ignored. Additionally, this paper aims to develop a graphical tool which intuitively, and simply, encodes this newly-established understanding. This tool should allow educators to sufficiently motivate statements like '...ignoring air resistance' without resorting to in-depth mathematical arguments, partially re-establishing students' confidence in the applicability of what they are taught in undergraduate physics courses.

There have been a number of previous explorations, within the context of physics education, of the effect of air resistance on falling bodies. Grant [9], for example, investigates the effect air resistance has on a variety of school sports involving projectile motion using a simple experiment. Kincanon [10] uses skydiving as an example for teaching about resistive forces. Using basic physical principles, a skydiver's speed as function of time is remarkably well reproduced. Agrawal [11] investigates the relation between a skydiver's mass and terminal velocity in the horizontal spread eagle position. Theilmann *et al* [12] and Greening [13] both investigate supersonic free fall, specifically discussing Felix Baumgartner's record-breaking jump, also known as the *Red Bull Stratos* space diving project. While both of these papers focused on the relationship between air density and air resistance, and the resultant effect on terminal velocity, Theilmann *et al* also modelled the free fall itself.

2. Graphs as effective conveyors of information

Graphs are powerful tools that can visually communicate complicated concepts in an approachable manner [14]. Their utility as conveyors of information has led some researchers to argue that correct understanding of a concept will more likely be developed if it is first introduced using graphical representations of its core elements, instead of mathematical representations (e.g. Jackson *et al* [15]).

When deciding how to best convey the important aspects of the physics described in this paper, it proved useful to draw inspiration from a similar situation: evaluating how significant relativistic gravity is for a given astrophysical system. In that case the magnitude of the effect of relativistic corrections is characterised by the ratio of two numbers associated with the system or object in question. In some textbooks, these graphs are used to very good effect to convey this characterisation simply to the student. As an example, Hartle [16, p 5] uses a graph of the characteristic mass versus the characteristic radius of various astrophysical (and everyday) objects to show whether relativistic gravity is necessary when describing them, or whether classical Newtonian gravity will suffice. An important addition made to this graph is that of a diagonal line whose slope corresponds to specific value for the ratio between an object's characteristic mass and radius. This diagonal line allows the reader to instantly, and intuitively, evaluate how significant relativistic gravity is for a given system, since relativistic gravity is more important for objects that lie closer this line.

This graph for relativistic gravity serves as the inspiration for the graphs we develop in this paper. As will be shown in section 3.2, the significance of air resistance similarly depends on the ratio between two characteristic parameters of an object: its cross-sectional surface area (A_c ; perpendicular to its motion) and its mass. Our approach is therefore to distil the physics of air resistance into a similar graph, which can serve as a tool with which students and educators can evaluate the significance of air resistance for a given system, and decide whether or not it is justified to ignore air resistance.

Before considering the development of this set of graphs we first investigate the physics of falling objects in more detail. While this investigation is crucial for developing the graphs, understanding and using them does not require an understanding of the physics described here.

3. The physics of falling objects

3.1. Free-fall motion

Objects falling only under the influence of gravity are said to be in free fall. In the one-dimensional case, their motion can be described

by a simple linear differential equation (from Newton's Second Law):

$$\frac{d^2s}{dt^2} = g, \quad (1)$$

where (d^2s/dt^2) is the object's acceleration, and s , t , and g have their usual meaning. Solving this equation is well within the reach of most first-year undergraduate students. Doing so requires only simple integration, and yields the well-known expression

$$s(t) = ut + \frac{1}{2}gt^2, \quad (2)$$

where u is the object's initial speed.

3.2. Drag-affected motion

The real-world projectiles students typically have experience of, however, also experience a drag force F_d due to air resistance [5]. To successfully describe the motion of objects for which this force is significant, then, we need to solve a modified version of equation (1):

$$\frac{d^2s}{dt^2} = g - \frac{F_d}{m}, \quad (3)$$

where m is the object's mass.

For an object moving with speed $v = (ds/dt)$ through air with density ρ , the drag force acting on it can be written as [5]:

$$F_d = \frac{1}{2}C_d\rho A_c v^2, \quad (4)$$

where A_c is the object's cross-sectional area perpendicular to its direction of motion, and C_d is the drag coefficient associated with that object. This force arises as a result of turbulence effects as air flows around an object. It is therefore only valid for objects that are large enough, and are moving fast enough, for these turbulence effects to become important. For most everyday objects more than ~ 3 cm across, equation (4) is a very good approximation of the drag force. The value of C_d is determined by the shape and smoothness of an object. In this discussion it is only important to know that, in general, smooth objects that have the same shape, have the same C_d , regardless of their relative size (as long as they are not too small). For the sake of simplicity, we will assume that all the objects considered here have the same value for C_d . Equation (3) therefore becomes:

$$\frac{d^2s}{dt^2} = g - \frac{1}{2}C_d\rho\left(\frac{A_c}{m}\right)v^2. \quad (5)$$

This differential equation is nonlinear in s (due to the v^2), and is therefore much more difficult to solve than its free-fall counterpart. The mathematical tools needed to solve such equations generally lie outside the scope of typical undergraduate courses, which inhibits the degree to which the effects of drag can be investigated. Fortunately, useful physical understanding regarding the effects of drag can already be extracted from equation (5) without solving it.

First, we can qualitatively understand how an object experiencing drag will fall, and how its motion will differ from free-fall motion. Initially, for an object dropped from rest, its acceleration is g , just as in the free-fall case. As the object accelerates, and v increases, the magnitude of the net acceleration it experiences decreases. Compared to the free-fall case, therefore, the object will fall less rapidly. Additionally, if the object is allowed to fall long enough, the net acceleration will become zero. The speed for which the net acceleration is zero, is the terminal speed v_t . Conversely, an object initially moving at a speed greater than v_t will decelerate (since the second term would be larger than g) until its speed is v_t .

Second, we see that the magnitude of the drag term in equation (5) is directly proportional to the ratio (A_c/m) . Therefore, if two objects have different values for (A_c/m) , they will fall at different rates. In the case where both objects have the same A_c , this boils down to something that closely resembles the alternative conception students report: the more massive object, having a lower value for (A_c/m) , will fall more rapidly.

This is, of course, in stark contrast with the free-fall case, where all objects fall at the same rate, regardless of their mass. Fortunately, this attribute of free-fall motion is not totally lost in the drag-affected case, and its analogue can be stated as: **all objects that have the same value for (A_c/m) fall at the same rate**. When trying to determine which model for the motion of a falling object is appropriate, i.e. under which circumstances air resistance can be ignored, this attribute of drag-affected motion proves to be quite useful.

3.3. When to resort to the drag-affected model

The two models described above are related in a very specific way: free-fall motion is a limiting case of drag-affected motion in the limit where $(F_d/m) \rightarrow 0$ (see equation (3)). Therefore, the free-fall model is perfectly valid to use in some cases, while the drag-affected model is more appropriate in others. There is, however, no clear-cut boundary between these two categories. This is problematic since students encounter both kinds of motion in their everyday lives, leading to confusion when confronted with statements like ‘... ignoring air resistance.’ Such statements therefore give students the impression that their everyday experience should be ignored when solving physics problems, and that what they learn in their physics courses does not apply in their daily life.

A good first step in addressing this issue is to enable the students to recognise which phenomena or systems fall into which category. Since we are trying to say something about things that they have observed, it is best to do this using quantities they can easily recognise from their experience. To this end, the boundary we define in this paper between the two regimes (free-fall and drag-affected) is based on the distance an object falls. Specifically, for an object dropped from a height h , we say that the drag-affected model is more appropriate if the object in question falls less than some fraction k of h in the time it would take a free-falling object to fall the entire height. Symbolically this becomes:

$$s_d(t_h) < kh, \quad (6)$$

where $s_d(t)$ is the object’s displacement as function of time for the drag-affected model, and t_h is the time it would take a free-falling object to fall a distance h . The specific choice for the value of k is less important, and a range of values could feasibly make sense. In our numerical method we chose a convenient value of $k = 0.95$, implying that a drag-affected object falls less than 95% of the height, to illustrate what we found.

This boundary definition connects directly to the reported alternative conception (that ‘heavier objects fall faster’), since two objects falling at different rates will fall different distances in the

same time. It also allows the construction of a very simple, and intuitive experiment to demonstrate how the two regimes differ (see section 4). Most importantly, we provide a tool with which the student can quantify the significance of air resistance in various everyday phenomena without solving equation (5). This is especially true within the context of an experiment, since students essentially obtain the solution to equation (5) empirically and compare it to the familiar free-fall solution (equation (2)).

This boundary definition is not complete, however, since we have not yet related $s_d(t)$ to parameters characterising different objects. As stated in section 3.2, the rate at which an object falls is inversely proportional to the ratio (A_c/m) . Since the object's displacement is merely the integral of its rate of fall, this implies that

$$s_d(t_h) \sim \frac{1}{(A_c/m)}. \quad (7)$$

Since the deviation between the two cases, for a given height, depends on $s_d(t_h)$, and $s_d(t_h)$ decreases as (A_c/m) increases, there has to be some value $\sigma_k(h)$ for (A_c/m) where $s_d(t_h) = kh$ (i.e. where equation (6) becomes an equality). Once this value is known for a specified height (and choice for k), we can easily know whether an object will display drag-effected motion or free-fall motion by comparing its (A_c/m) to it. Stated mathematically, the drag-effected model is appropriate if

$$\frac{A_c}{m} > \sigma_k(h). \quad (8)$$

In section 5 we present a graph that demonstrates how this condition translates to a useful tool with which to evaluate the significance of air resistance for a given system. We also give an empirical form for $\sigma_k(h)$ based on our numerical solution of equation (5).

4. The numerical method

Our initial attempts to produce useful approximate solutions to equation (5) by means of proportional reasoning, specifically attempting to estimate the time an object would take to fall a given distance, proved unsuccessful. Our attempts especially failed to enable a satisfactory evaluation of

whether air resistance was important for a given situation. Eventually it became evident that our initial choice to characterise the motion's deviation from free-fall motion by a deviation from the free-fall predicted fall time, was a bad one. This was due to the fact that for a given fall time deviation, the displacement deviation depends on the speed of the object at the end of its motion. For a light object, like a feather, which typically moves slowly at impact, a deviation of 0.5 s is small from a height of 2 m, while for a heavy object, like a bowling ball, which typically moves much more quickly at impact, a deviation of 0.5 s is large.

Our final choice, to characterise an object's motion rather by the deviation in its displacement, proved more effective. To obtain this result, equation (5) was numerically integrated by means of a *finite difference method*. First, the integration was transformed into a summation by discretizing the time t . The problem then reduces to an iterative calculation, with each iteration corresponding to an incrementing of t by a finite time difference Δt . At each of these steps, the instantaneous acceleration a , and instantaneous speed v , are calculated, and the latter is used to estimate the distance the object falls during the interval Δt . For the i th iteration, these quantities are calculated, in order, as follows:

$$\begin{aligned} a_i &= g - \frac{F_{d,i-1}}{m}, \\ v_i &= v_{i-1} + a_i \Delta t, \\ s_i &= s_{i-1} + v_i \Delta t. \end{aligned} \quad (9)$$

where the subscripts i and $i - 1$ refer to the values for the subscripted variable for the current and previous iteration, respectively, and $F_{d,i-1}$ is the drag force defined in equation (4) for v_{i-1} . For the first iteration the initial conditions for a ball falling from rest are used as the ' $i - 1$ ' values. These initial conditions are $v_0 = 0$, $s_0 = 0$, and (in the interest of consistency) $a_0 = g$.

Upon completing this integration for a given ball and height, we are left with a numerical solution for $s_d(t)$. This solution can then be compared to the prediction for free fall, and the condition defined in equation (6) can be checked for that motion (telling us whether or not the motion is significantly drag-effected). Doing this for a variety of balls, each having a different value for (A_c/m) , dropped from a range of heights,

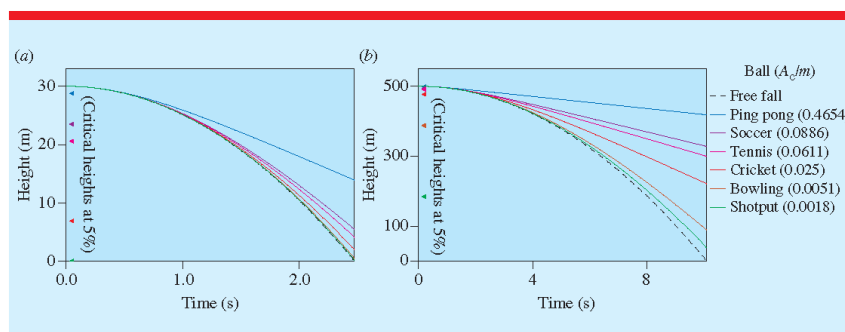


Figure 1. Simulated trajectories for a variety of balls dropped under the influence of air resistance from two different heights: 30 m and 500 m. The dashed line indicates the trajectory predicted for free fall. For each ball, the height at which its displacement deviates by 5% from free fall is indicated with a $\triangle$. (a) $h = 30$ m, (b) $h = 500$ m.

then allows us to estimate the function $\sigma_k(h)$ we defined in equation (8).

In practice the estimation of $\sigma_k(h)$ was done by dropping a set of test balls numerically (as described above) by means of a Python implementation of the numerical calculations detailed here. Python is a high-level programming language designed to be both easily human-readable and powerful. These balls all had the same radius (and therefore equal A_c), but their masses were chosen such that the effect of drag decreased linearly as the balls' masses increased. The solutions for $s_d(t)$ obtained for this set of balls were then used to estimate the value of (A_c/m) where $s_d(t_k) = kh$ for a set of heights (1 m, 10 m, 100 m, and 1 km). From these calculations the results in section 5 were produced.

5. Results

Using the numerical method detailed in section 4, two sets of graphs and an empirical solution to $\sigma_{0.95}(h)$ were produced. Figure 1 shows the trajectories of a variety of balls as predicted by the drag-affected model. These trajectories initially closely resemble those predicted by the free-fall model (the dashed line). As the balls fall, their trajectories increasingly deviate from free fall, with the degree of deviation determined by the (A_c/m) ratio associated with each ball. Figure 1 shows that higher values for (A_c/m) correspond to more severe deviations. In figure 1(b) we also see that the balls' trajectories tend toward straight lines as they fall. This corresponds to the balls reaching

their terminal speed, and the slope of their trajectory once it's straight is its terminal speed. Lastly, by comparing figure 1(a) to (b) we see that the deviation monotonically increases for any ball as time passes, just at varying rates.

In figure 2 a variety of balls are plotted according to the A_c and m values, along with a set of straight lines corresponding to different values of $\sigma_{0.95}(h)$ (for the sake of clarity this graph is plotted at two different zoom levels). For any such line, corresponding to a specified drop height, the drag-affected model is appropriate for balls that lie above it, and the free-fall model for balls that lie below it (in accordance with equation (6)). As the drop height is increased, the slope of the corresponding line decreases, and an increasing number of balls become drag-affected. At a drop height of 400 m all the balls in our sample are drag-affected.

For balls that have similar sizes (comparable A_c ; e.g. the Tennis and Cricket balls), we see that lighter balls are more greatly effected by air resistance. This behaviour corresponds well with what the reported alternative conception predicts: that heavier objects fall faster.

Table 1 gives the empirical solution obtained for $\sigma_{0.95}(h)$.

6. Discussion

Figure 2 shows the conditions under which the effect of air resistance cannot be ignored. As discussed earlier, the critical ratios ($\sigma_k(h)$) for the different heights are related to the

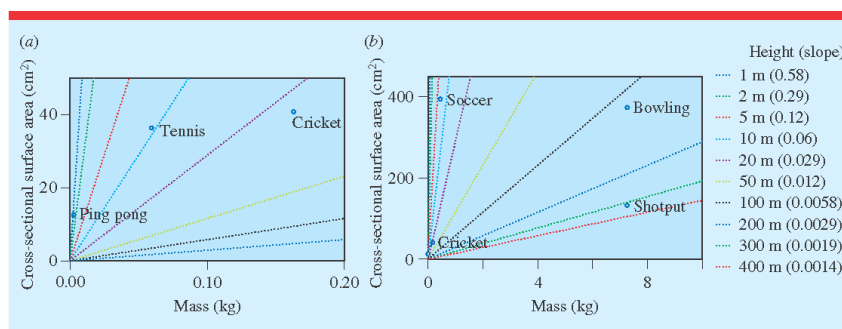


Figure 2. Graphs of A_c versus m for a variety of balls. The dotted lines each correspond to a drop height, and indicate the boundary between free-fall and drag-affected motion for that height. For such a line, if a ball lies above it, that ball's motion is best described by the drag-affected model when dropped from that height. This means that their displacement will deviate by more than 5% from free fall when dropped from the corresponding height. Balls that lie below a given line, are well described by free fall when dropped from the corresponding height.

slopes of the lines. The position on the graph of a given ball relative to one of these lines determines whether that ball is best described by the free fall or drag-affected model when dropped from the corresponding height. If the ball lies above the line, the effect of air resistance is large enough to warrant the use of the drag-affected model. To understand this relation, consider the most massive ball in the study, the shotput. This ball lies above the 400 m line, but below the 200 m line. The (A_c/m) ratio of 0.0018 for the shotput is smaller than the critical ratio of 0.0029 for the 200 m line, but larger than the critical ratio of 0.0014 for the 500 m line. This means that the shotput's displacement will deviate by $<5\%$ from free fall when dropped from 200 m, but by $>5\%$ when dropped from 400 m. Consequently, for the latter case the drag-affected model is more appropriate (for our chosen tolerance)

This behaviour can be summarised as follows: (i) the lower the (A_c/m) ratio is, the less significant the effect of air resistance on the object, and (ii) if the (A_c/m) of a ball is more than the critical ratio for a certain height (i.e. if the ball lies below the corresponding line) the effect of air resistance can be ignored.

6.1. Revisiting students' alternative conception

Examples used to introduce and assess the concept of free fall typically describe the motion of two objects (usually equally sized balls with different

Table 1. The obtained values for $\sigma_k(h)$ at various drop heights for $k = 0.95$. The value of $\sigma_{0.95}$ at a given height is the maximum allowed value for the ratio (A_c/m) a ball may have to still be considered as in free fall under equation (6). Air resistance is important, at a given height, for any object with $(A_c/m) > \sigma_{0.95}(h)$.

Height h (m)	$\sigma_{0.95}(h)$ ($\text{m}^2 \text{kg}^{-1}$)
1	0.58
2	0.29
5	0.12
10	0.06
20	0.029
50	0.012
100	0.0058
200	0.0029
300	0.0019
400	0.0014

masses) being dropped simultaneously from the same height (see for example Item 1 of the Force Concept Inventory presented in Hestenes *et al* [17]). If a student who believes that heavier objects fall faster is asked to predict which ball will hit the ground first in such an example, ignoring air resistance, they generally answer that the heavier of the two balls will hit the ground first.

The qualification of equal sizes for the balls, i.e. equal A_c , is never emphasized, and students consequently do not consider it to have an influence on the motion. The cross-sectional area plays an equally important role in the determination of the motion, however. Discussions regarding its impact are generally limited to specific examples, e.g. a parachutist experiencing an increase in drag

when he opens his parachute. These examples usually intend to illustrate the concept of terminal speed, and neglect to point out that both mass and cross-sectional area are important when considering the magnitude of the experienced drag force. For example, in comparing the motion of a leaf and a nut falling from the same tree and the nut landing first, the difference in motion is more often explained in terms of the bigger mass of the nut than in terms of the bigger cross-sectional area of the leaf.

Having little or no knowledge of drag, students do not realize that a heavier object is less restricted by drag while a bigger object is more restricted by drag, and that the real falling rate (along with the drag coefficient) is determined by the ratio of these two quantities. As a consequence, students tend to focus on the influence mass has on the motion, concluding that heavier objects fall faster.

6.2. Addressing their alternative conception

Figure 2 (either (a) or (b)) captures the essence of the constraint derived in equation (8), and provides an easy-to-use tool with which to determine whether air resistance is relevant for a specific circumstance. Included in an undergraduate physics text, such a graph would provide an invaluable reference against which to justify the qualifying phrase ‘... ignoring air resistance’ throughout the text. With little more than a brief introduction to how this graph is to be used, a student can easily assess and understand why air resistance can be ignored for a given problem. Additionally, this graph serves to assure the student that the physics they are being taught is indeed applicable to their everyday experience.

7. Conclusion

The physics argument in this paper enriches the concept of free fall and provides a comprehensive explanatory framework that encompasses both idealized and observable situations. The study validates the use of the conditional statement ‘... ignoring air resistance’ by providing convincing evidence that there are circumstances when, although present, the effect of air resistance can realistically be ignored. We also illuminate two factors that influence the effect of drag on falling balls, namely the falling height (h) and the cross-sectional area to mass ratio (A_c/m). The most

valuable contribution of the study is the graph in figure 2, which captures this conceptual understanding in a very simple and concise way.

8. Implications for teaching

An advantage of the approach described above is making students aware of how one abstracts real-world phenomena into theoretical framework, and how simplifying assumptions like the one they generally encounter regarding motion through air, come about. In essence, it shows them when to disregard certain aspects of real-world problem without losing the desired applicability, and when not to. Students’ real-world alternative conception that ‘the heavier ball falls faster’ is not discredited, but used for meaning-making by relating the practical and theoretical worlds. This, in turn, enhances students’ view of physics as a collection of coherent concepts, applicable and valuable in their daily lives.

The study has another very important implication for the teaching of Galilean free fall. The graphical representations offer a way for both students and teachers to interpret and understand the conditions under which this principle is valid. The condition of free fall facilitates the learning of other physics topics, e.g. conservation of energy and projectile motion and also serves as an example of the application of conditional statements elsewhere in physics.

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CHAPTER 9: CONCLUSION

9.1. Introduction

In this chapter a summary of the research presented in this thesis is presented. A very brief overview of the literature chapter is given, followed by an outline of how DBR was used in this study. The research questions for each one of the DBR iterations are addressed in terms of the results of the study, followed by the refined design principles as they emerged from the research. I conclude the thesis with the implications of the results for teaching introductory mechanics and suggestions for future research emerging from the study.

9.2. The central conclusions of the literature review

In Chapter 2 a review of literature on some broad constructivist issues about learning and learning physics has been presented. The nature of physics knowledge and the influence of inherent student beliefs about physics concepts on their understandings of those concepts, and on their future learning, has been emphasized. Issues concerning specific kinematic- and dynamic- aspects of introductory mechanics have been discussed. The importance of conceptual change in student understanding and the common failure of conventional teaching approaches to foster student conceptual change have been justified by extensive reference to the large existing body of literature.

In summary; this review demonstrates the interlinkages between student perspectives on what physics is, how it may or may not be seen to apply to their daily lives, and the outcomes of more effective ways to teach the fundamental concepts and relationships by using and building on what students already know. These interlinked ideas formed the fundamental platform on which this study is based. One core problem in teaching introductory mechanics is that most of the past approaches to fostering student conceptual change have had limited success. This critical aspect of the literature supported my central argument that, in the pursuit of greater success than as yet achieved in fostering greater student understanding, we need to look at a much more fine-grained detail of both the sequencing of physics concepts and the learning and teaching of this content.

9.3. Summary of the application of Design-Based Research approach in this research

The justification for using DBR in this study has been presented in Chapter 3. A summary of how the different iterations in my use of DBR aligned with the central characteristics of DBR described by Wang and Hannafin (2005), follows:

- The DBR process is pragmatic; its goals are solving current real world problems:

The central problem for which I was using DBR was the remarkably persistent alternative conceptions regarding motion under gravity namely that heavier objects fall faster, that inhibit student conceptual understanding of the concept of acceleration and gravitational acceleration in particular, and the consistent failure of past attempts to foster greater student understanding in this aspect of mechanics.

- The DBR is grounded in the real world context:

My successive interventions were done in the “messiness of real world practice” with the complexities, dynamics and limitations of authentic practice, and with post-school students who were genuine learners of these concepts and who were in authentic class situations.

- DBR is interactive, iterative and flexible:

Wang and Hannafin (2005) characterised DBR as interventions to be continuously developed and refined through an iterative design process from analysis to design to evaluation and redesign. In correspondence to this description each iteration in this research study was informed by the evaluation, analysis and revision of preceding iterations (and, particularly for the first iteration, by the results of previous relevant research). As noted in the first dot point above, the common concept in all the iterations was seeking to understand the circumstances that will foster better understanding of the specific mechanics relationships and concepts that are poorly understood for motion under gravity. The resulting approach toward acceleration as the net force to mass ratio informed the content of the subsequent iteration, which in turn informed the next iteration as required.

- The DBR is evaluated and its merit is measured by its usefulness in practice:

Wang and Hannafin, (2005:6) argue that “the merit of DBR lies in its usefulness for practice” i.e. the extent to which it improves educational practices through implementation. The worth of DBR to render improved educational practices through implementation of the iterations is supported by the practical significance of the conceptual teaching approach to clarify the simplifications in the physics *per se*, the value of approaching acceleration as the net force to mass ratio and the set of graphs developed to clarify explanation of the effect of air resistance. These outcomes have indicated that the DBR results have value in content domains beyond this research.

In the next section I link the iterations of the DBR in the sequence in which they were conducted with the refined design principle[s] that applied to each particular iteration.

9.4. Reflection on iterations and refinement of the design principles that underpinned the DBR

Reflection on the results of the iterations lead to refinements of the design principles that underpinned/were emphasized in each iteration. The design principles, which can serve as guidelines for designing fine grained instructional practices to teach specific physics concepts, are explained below in terms of the iterations of this DBR:

- Design principle 1: *Constructivist approach: Determine what student current conceptions and knowledge are and build on that.* In Iteration 1 student current conceptions were determined by using paired questions in which the context of each member of a pair differed in terms of the direction of motion and/or the physics variable to be solved. In Iterations 2 to 4 student current conceptions were revealed by instigating cognitive conflict. For iterations 2 to 4 Design principle 1 was extended to use current conceptions and knowledge as anchors to build new knowledge on.
- Design principle 2: *Considering the links between the real and the physics worlds presented in the form of conditional statements* serves to counter student perceptions that physics concepts are unrelated and only apply to specific individual situations. In Iterations 2 to 5 the condition of *in the absence of air resistance* and the logical operations it implied had been discussed and explained. Design principle 2 was extended to include considering the extent to which simplification complicates student learning and proposing a demonstration and a set of graphs as solutions to this problem.
- Design principle 3: *Identify core concepts in the content material that need to be enhanced, including concepts that students may never have thought about (e.g. threshold concepts, alternative conceptions, missing conceptions).* Not only should students understand underlying concepts, but also they should know when and where these concepts apply. For Iteration 2 fundamental concepts, such as net force, that are related to the threshold concept of acceleration were emphasized. The web of connected concepts was elaborated to include concepts that students might not have considered, such as terminal velocity and air resistance. For Iteration 3 to 5 the concept of acceleration had been reconceptualised as the net force to mass ratio.
- Design principle 4: *Establish conceptual coherence in physics knowledge.*

Physics is a connected web of knowledge, a network in which linking the relationships are as prominent as the discrete bits of information. Two forms of coherence that are needed for “conceptual coherence in physics” are coherence across the concepts of physics and

coherence across representations used in physics. Each of these forms is now considered separately.

- i) Coherence of concepts: Physics concepts should be introduced from a conceptual qualitative approach rather than from a mathematical approach.

In Iteration 2 the concepts related to acceleration, particularly gravitational acceleration, were linked qualitatively. For Iterations 3 and 4, acceleration was modelled from a force to mass ratio or dynamics perspective instead of the mathematical time derivative of velocity perspective as currently is the norm in South African schools and universities. The arguments identified for following the dynamics approach (introducing acceleration focusing on developing qualitative reasoning around the force to mass ratio, followed-up with a mathematical approach by introducing $F_{net} = ma$ and then the time derivative of velocity approach) include:

- It is aligned with the spirit of Newton's second law of motion;
- It affords opportunities to reason with and about the quantities and their relationships present in the expressions; and
- It encourages conceptual development and change.

- i) Coherence across representations: In addition to having reconceptualised acceleration as the net force to mass ratio in Iteration 3, in Iteration 4 motion diagrams were identified as being critical additional representations in qualitatively relating the various physics concepts that are usually quantitatively represented by equations. The linking of various representations in a physics system purposefully selected/designed for a specific physics concept can enhance student understanding of the coherence between physics concepts. Science teachers need to know which representations are critical for understanding the material they wish to teach and in what sequence they have to be included to achieve their pedagogical goals.

In the sections that follow I indicate how the refined principles emerged in the different iterations.

9.4.1. First iteration: Exploring the extent of the research problem

The results of the first iteration conducted across three consecutive years, indicated that the conditional statement 'in the absence of air resistance and/or friction' revealed the alternative conception that heavier objects fall faster among the majority of first year undergraduate physics students. While such statements simplified the teaching of physics concepts, they did not simplify the learning of these concepts – refer to section 2.6.2. The need to consider and discuss

conditional statements and simplification for future learning has been highlighted by the results of Iteration 1.

9.4.2. Second iteration: Enhancing conceptual coherence

In an attempt to find a solution for the difficulties caused by simplification, the second iteration was guided by the following detailed questions: To what extent does a) explanation of conditional statements and b) the use of multiple representations of motion in different contexts contribute to student understanding of i) the concept of net force and the acceleration associated with net force, and ii) the conceptual relationships between the physics variable for motion under gravity?

While the second iteration included an explanation on the use of conditional statements, the focus was more on the consequences of such conditional statements, namely if air resistance and friction were ignored, then all objects moving under gravity alone would have the same acceleration. The use of multiple representations revealed that motion diagrams, as used to visualize equal acceleration for different objects, contributed to a large extent to the student linking of different representations, including equations, in a qualitative manner. This in turn increased conceptual coherence of physics concepts and representations. The use of motion diagrams as a way to represent the equal acceleration caused by gravity as the net force pointed towards the need to relate acceleration more closely with the effect of an applied force on an object's motion, namely, the net force to mass ratio. The effect of this conceptual approach to acceleration was therefore the focus of iteration 3.

9.4.3. Third iteration: A conceptual approach to teaching acceleration

The detailed research question guiding this iteration was: What is the effect of an alternative teaching approach to acceleration as the net force to mass ratio on i) student understanding of the concept of acceleration and ii) student use of qualitative proportional relationships of Newton's second law? The qualitative results from the approach to teaching acceleration as a conceptual proportionality (acceleration as the net force to mass ratio) have pointed towards an improvement in student conceptual understanding of acceleration and the proportionality between the net force exerted on an object and its mass. However, these results also emphasized student difficulties to relate different physics quantities through qualitative and/or proportional reasoning.

The evidence obtained in this iteration indicated that including the conceptual approach to acceleration as the net force to mass ratio had a practically significant effect in enhancing the student conceptual understanding of the force-acceleration relationship of a moving object, with gains of between 20% and 70% in correct answers compared to the correct answers from the pre-test. This evidence linked to the results obtained in previous iterations of the research study

that explaining conditional statements and clarifying the consequences of such statements in a conceptual approach to acceleration contributed to student conceptual understanding.

9.4.4. Fourth iteration: Introducing equations as reasoning tools

The detailed research questions for this iteration were: i) How will an approach, consisting an alternative representation of acceleration as the net force to mass ratio, influence students' conceptual understanding of the concept of acceleration; ii) How will blending of representations (see footnote Section 1.7.7) and introducing equations as reasoning tools in qualitative reasoning influence student understanding of the conceptual relationships represented by equations? The practically significant results from inferential statistical analyses give evidence that both the alternative approach to acceleration as the net force to mass ratio and the blending the affordances of representations indeed enhanced student conceptual understanding of the acceleration of an object.

This evidence links to the results obtained in previous iterations of the research study that explaining simplification statements, clarifying the consequences of such statements and implementing qualitative reasoning enhanced by the use of motion diagrams contribute to student understanding of conceptual relationships. Research on the effect of introducing qualitative reasoning in particular to undergraduate first-year physics students is continuing as a project in collaboration with two other universities in South Africa. The results from this ongoing project are not included in this thesis.

9.4.5. Fifth iteration: Simplification – when is it reasonable to ignore the effect of air resistance

The detailed research question for this iteration was: What are the specific circumstances under which it is realistic to ignore the effect of air resistance on falling bodies? The problem concerning simplification was identified in Iteration 1 and explained in Iterations 2 to 4. In this iteration (Iteration 5) I provided an in-depth solution to this problem by explicitly relating real life and physics conditions. In cooperation with a colleague at the Centre for Space Physics at the North-West University, where this research has been executed, graphical tools with which the student can find data about the significance of air resistance in various everyday phenomena have been developed. One of these graphical tools contains boundary values for a variety of heights of fall, which makes it possible for students to decide whether the motion of a ball dropped from the specific height can reasonably be considered as free fall or whether air resistance ought to be considered. This iteration, presented in Chapter 8, was the topic of an article published in 2017

(Ferreira, Seyffert *et al.*, 2017) and a presentation at the European Science Education Research Association 2017 conference in Dublin, 21 – 25 August 2017.

9.5. Addressing the research question

The problem that initiated the research was that conditional statements, intended to simplify physics questions, invoke student alternative conceptions and inhibit development of understanding of conceptual relationships in this particular domain of introductory mechanics. The main research question, “What circumstances will foster better understanding of specific concepts and conceptual relationships regarding free fall, that are poorly understood?”, emerged from the research problem. The results from the different iterations revealed that the circumstances influencing understanding of relationships and concepts are embedded in the research problem, namely, conditional statements, simplification of problems, alternative conceptions and conceptual relationships. In addition to identifying circumstances that will foster better understanding of specific relationships and concepts that are poorly understood, this research incorporated those circumstances to develop a conceptual approach towards teaching for understanding of the concept of acceleration.

The core difficulty addressed was that only limited success had previously been obtained with a range of attempted solutions to the commonly demonstrated difficulties students experience when learning about acceleration and motion in free-fall. The circumstances for enhanced conceptual understanding of poorly understood relationships and concepts concerning free fall that my study focused on are:

- Considering the impact of using conditional statements to simplify teaching but increasing difficulty of learning physics;
- A conceptual rather than kinematic approach to teaching acceleration;
- Using multiple representations and identifying *critical*² representations to enhance understanding of conceptual relationships; and
- Qualitative (proportional) reasoning / using equations as reasoning tools.

While I have applied a range of teaching strategies (e.g. inquiry, cognitive conflict, POE, experimentation, simulations) in my study, I did not investigate any of them *per se*. My study dealt with specific problems that students have in getting to know physics and its epistemology. Hence,

² Representations which are crucial to understanding a specific concept and without which understanding would be unlikely

I investigated possible solutions from a physics perspective (top-down), while attending to students' difficulties (bottom-up), as summarized in Table 9-1 below.

Table 9-1: Student problems and circumstance for enhanced understanding

Students' problems	Circumstances for enhanced understanding
1. Students perceive physics as disconnected from the real world	Clarification of simplification as a core difference between real world and physics situations, and when and why simplification is used. Use a constellation of representations: from real world situation, to conceptual models (motion diagrams), to formal models (equations and graphs).
2. Algorithmic problem solving is frequently rote	Qualitative reasoning Use physics equations as reasoning tools
3. Persistent conceptual difficulties regarding the concept of acceleration (core concept in mechanics that links kinematics and dynamics), especially in free-fall situations.	Alternative sequencing (The conceptual approach involves all above-mentioned circumstances – simplification, qualitative proportional reasoning, and multiple representations)

Every iteration of the DBR investigated a combination of these circumstances, as illustrated in Figure 9-1.

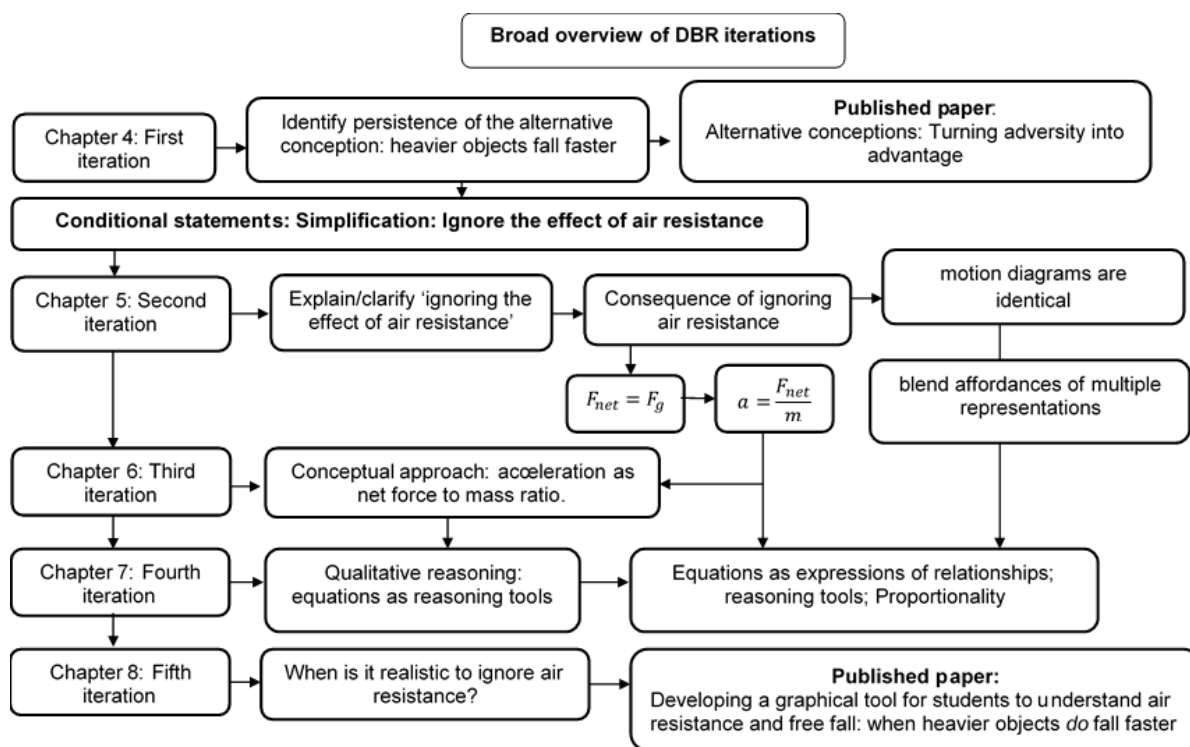


Figure 9-1: Broad overview of the iterations of this DBR study

Considerations of the simplification of physics *per se*, i.e. the use of conditional statements, formed part of iterations 2 to 5 (because this connection between real world and physical systems is so fundamental and crucial, and almost always not clarified). Furthermore, there is progression regarding considerations of simplification from the second iteration (where its role is hypothesized) to the use of the graphic tool in the fifth iteration. Qualitative proportional reasoning has been used to justify the acceleration as net force to mass ratio approach, applied experimentally to deduce the proportionalities of Newton's second law and expanded towards the more general use of equations as reasoning tools. Combining the affordances of multiple representations has been helpful in emphasizing the coherence of physics concepts.

In implementing the intervention, it is important to note that the specific activities, strategies, sequence of implementation and emphasis of circumstances are very much context bound. For example, the demonstration with the falling paper cups and the balls is appropriate for physics students at any level, from school to B.Ed. Honours level. The graphs developed in the last iteration on the other hand, require graph comprehension that high school students have not yet acquired and that is not expected from first-year non-calculus-based physics students. For teachers enrolled for the B.Ed. Honours module both activities on simplification, the demonstration of the falling cups and the graphs and interpretation thereof, can be done. Although the alternative conceptual approach regarding acceleration is highly recommended, it may be difficult to implement in schools due to the curriculum that prescribes a rigid progression of the

sequence in which concepts must be taught. The intervention encompasses different ways and levels of representing and sequencing the circumstances applicable to a physics situation. The extent to which the circumstances applicable to a physics situation influence student understanding, depends on the academic level, the course the students are enrolled for and external factors such as the prescribed curricula. Therefore, the intervention should be included in teacher training programmes. Figure 9-2 below presents a diagrammatic summary of the progression of the intervention executed in the research.

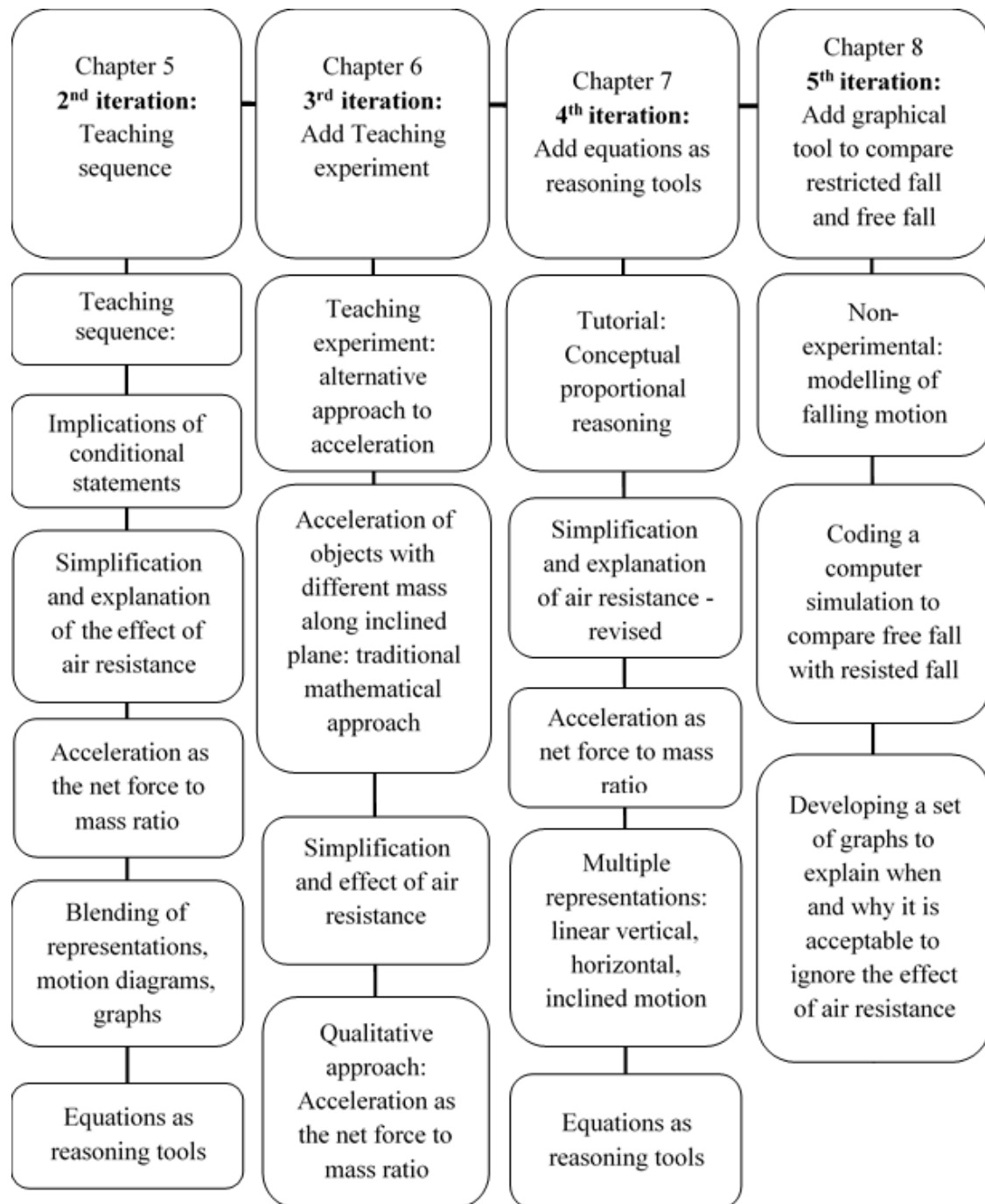


Figure 9-2: Progression of intervention

9.6. Conclusion and contribution of the research

There had been many attempts to try and better understand possible approaches that may improve student understanding of “motion under gravity” over the last 30 plus years with little success. The significance of this thesis is to have explored a novel approach which had not been considered before and which has resulted in promising increased understanding of how to help students learn these concepts and relationships.

To conclude the DBR, I reconsider and attempt to answer the two rhetorical questions posed in Chapter 3: i) What does the intervention[s] tell us that might be useful for other contexts/problems beyond the specific content of the DBR research? The major contribution of this thesis is emphasizing the need to seriously recognise that conditional statements impact on learning physics. While conditional statements make teaching easier, the assumption that it also makes the learning of physics easier is unfounded. In fact, the evidence shows that conditional statements very frequently make learning physics harder.

ii) How does the intervention[s] result in a better understanding of the important and practically embedded problem which was the reason for undertaking a DBR study in the first place? The thesis responds to confront this core, unrecognised problem in proposing significant ways in which we can foster understanding of relations and concepts in free fall motion.

9.7. Research contributions

The following list summarises the main contributions of this thesis:

1. Circumstances identified to foster and enhance conceptual understanding of poorly understood relationships and concepts concerning free fall that this thesis focused on are:
 - The impact of using conditional statements; statements which are meant to simplify teaching, but which increase the difficulty of learning physics;
 - A conceptual rather than kinematic approach to teaching acceleration;
 - Using multiple representations and identifying critical representations to enhance understanding of conceptual relationships; and
 - Qualitative (proportional) reasoning / using equations as reasoning tools.
2. The resource (graphical tool) developed to assist physics teachers/students to make decisions around the validity of ignoring air resistance.
3. A set of design principles to inform the design of instructional practices that are fine grained enough to address the gap between physics educational research and instructional practices (refer to Section 9.4).

9.8. Research emerging from this study

Two research projects that emanate from the study in this thesis have already commenced. One is a research project involving staff from three universities in South Africa that is currently being undertaken to develop a teaching sequence on the influence of equations as reasoning tools. The study has already been piloted and is intended to be implemented as part of the regular curriculum and teaching approach during the 2018 undergraduate mechanics module at two of the universities. The second project involves extending the conclusions of this present study regarding conditional statements and the likely impact of these on physics learning. This involves addressing alternative conceptions, simplification and conditional statements continuing in the topics of momentum and magnetic fields and magnetic forces. It is foreseen that this continuing research program will later evolve to embrace consideration of student alternative conceptions and conceptual difficulties in more advanced physics topics.

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APPENDIX A: INVESTIGATING STUDENTS' CONCEPTUAL UNDERSTANDING THROUGH SOLVING KINEMATIC PROBLEMS IN VARIOUS CONTEXTS

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Abstract: Students' perceptions of the nature of physics knowledge affect their understanding of physics and the relevancy they attribute to concepts and principles to explain phenomena and solve problems to make sense of the natural world. Conceptual understanding of mechanics and the basic Newtonian concepts provides the foundation on which more advanced physics and engineering courses are built. It is crucial that students develop sufficient conceptual understanding of physics concepts to enable them to explain daily events from a scientific point of view and implement physics knowledge as a coherent web of ideas which applies to all walks of life. However, research reports deficiencies in students' conceptual understanding and ability to apply physics knowledge in unfamiliar contexts, even after tertiary education is completed. In this study we investigate the extent to which directions and planes of motion as different contexts in problem settings influence students' reasoning on idealized theoretical linear motion, and the implications of such influence. A multiple-choice questionnaire consisting of isomorphic problem pairs with the same underlying principle but set in different contexts, was designed and was completed by 481 university students in a first-year physics course on Newtonian mechanics. The questionnaire was followed by interviews with four randomly selected students. The results show that the direction and/or plane of motion affects the knowledge framework students invoke when they solve problems on idealized theoretical linear motion. The difficulty posed by conditions such as 'in the absence of air resistance and friction' is illuminated. This study provides insight into what students perceive as different contexts and also shows, for the first time, that the challenges posed by context can be used to effectively evaluate conceptual understanding of the net force–mass–acceleration relationship as defined in Newton's second law of motion.

Keywords: conceptual understanding, context, direction of motion

INTRODUCTION AND PROBLEM STATEMENT

Despite having a substantial body of empirical research on students' conceptions, mechanics remains a difficult domain to teach and to learn (Duit, Schecker, Höttecke & Niedderer, 2014). Students' ability to generalize principles to various situations and develop a working knowledge of basic concepts in mechanics is an important goal in physics education. Conceptual understanding of and the ability to apply the basic Newtonian concepts in introductory mechanics courses is essential for laying the foundation for advanced physics and engineering courses (Hedge & Meera, 2012). Even though physics is based on only a few concepts many students fail to see physics knowledge as a coherent structure (Singh, 2007). Students' misconceptions about the nature of science—e.g. the belief that science comprises of incontrovertible absolute truths as opposed to scientific knowledge that is subject to change and involves the invention of explanations, contribute to their difficulty to apply concepts and principles to explain phenomena and solve problems to make sense of the natural world (Ledermann & Ledermann, 2014). When students understand physics concepts, they are able to solve problems and, when they see physics knowledge as a coherent web of ideas which applies to all walks of life, they can predict and explain various phenomena scientifically (Muis & Gierus, 2014; Ogilvie, 2009). Despite the recognized importance of the development

of conceptual understanding, research in physics education shows that only few students are able to explain daily events from a scientific point of view, even after completing standard mechanics courses successfully.

THEORETICAL FRAMEWORK

Students' epistemologies (i.e. their perceptions of the nature of science and the nature of physics knowledge in particular) may affect their understanding of physics (Duit et al., 2014; Hammer & Elby, 2003). Students' epistemologies with such impact include the perceptions of physics as a set of disconnected facts and formulae, of formulae as expressions of interconnected concepts, and of physics learning as absorption of information (Lising & Elby, 2005). While physicists use concepts and principles to explain phenomena and solve problems to make sense of the natural world, many students try to find correct answers by plugging numerical values into equations that they often do not conceptually understand (Hutchison & Hammer, 2010). Daily life similarities in the observable features of associated phenomena usually determine intuitive mental categories. Physicists instead look for physics principles shared by phenomena that students may regard as dissimilar (Goldstein & Sakamoto, 2003).

Students' epistemic beliefs and alternative conceptions

Every student in introductory physics has a system of beliefs about physics based on their everyday-life observations (reviews of students' epistemologies and related research are found in Duit et al., 2014; Ledermann & Ledermann, 2014). Disagreement between these beliefs (experiential knowledge) and the formal scientific explanations often results in students' distorted comprehension of physics concepts. These distortions are among the principle causes of students' failure to achieve understanding in science (two extensive reviews of this and related research are found in Driver and Erickson, 1983; Gilbert and Watts, 1983). For example, many students correctly answer that in free fall objects of different mass will fall at the same rate, but when they have to apply the same concept (i.e. free fall) for the objects projected upward, they are unable to do so correctly. Even when students believe that they are learning about the real world when they study physics, failing to connect physics to their daily lives may result in their perception that the physics concepts have little relevance to their personal experience (Von Aufschnaiter & Rogge, 2015).

While physics phenomena are idealized, or cleaned of distracting factors when introduced to high school or undergraduate students, real-world phenomena are influenced by multiple and complex parameters which often require advanced mathematics for prediction or measurement of those phenomena (Duit et al., 2014). The high degree of mathematization, failure to specify what counts as explanations and the lack of clarification of what theoretical perspectives comprise, contribute to students' perception that physics is difficult. Contextual or 'everyday' physics problems are almost always simplified by cleaning it of elements such as friction or air resistance. Although disregarding such real-world factors in physics problems allows the use of physics equations involving uncomplicated mathematics, without sufficient clarification, the idealized scientific concept conflicts with students' experiential knowledge. Students consequently believe that the underlying principle does not occur naturally in the everyday world, nor is it relevant to their daily lives (Gunstone, 1987).

Evaluating conceptual understanding

The reported context dependence of students' epistemic beliefs, highlights the fundamental role that context plays in the physics learning process (Muis & Gierus, 2014; Gunstone & White, 1981). Students' lack of conceptual coherence of physics and their poor performance on contextual problems indicate conventional instruction's failure to identify or address ineffective tuition practices (Osborne, 2013; Von Aufschnaiter & Rogge, 2015). Such

findings of research shows the need to develop tools that differentiate between students' conceptual knowledge and conceptual understanding (Rebello & Rebello, 2011).

A way to evaluate concept development is to compare various similar situations (isomorphic situations) including situations in which students will likely fall back on their naïve knowledge while applying the same concept (Minstrell, 1982). Using isomorphic situations in research brings out the nature of student beliefs, reveals the existence of student misconceptions — or alternative conceptions — and clarifies the reasoning behind those misconceptions (Singh, 2007).

Direction and plane of motion

Information on the influence of the direction or plane of motion as separate contexts in student applications of kinematics concepts is limited. An extensive literature search found no research that statistically compared inclined plane motion, vertical motion in opposite directions and horizontal motion. Research on students' applications of alternative conceptions of force–acceleration–motion relationships, however, revealed that the direction and plane of motion play a role in student reasoning (Palmer, 1997, 2001; Lemmer, 2013). Palmer (2001) reported on students' perception that gravity acts on objects moving vertically downwards but not on objects projected vertically upwards. This supported his earlier report (1997) that students associate the direction of motion with the direction of the force. The earlier results (1997) indicated that the effect of a force opposing motion was applied more correctly in horizontal than in vertical motion. Lemmer (2013) presented evidence that student reasoning differed for motion in horizontal versus vertical downward plane, but were consistent for motion up and – down an inclined plane.

We conducted this study to investigate the effect of direction and plane of motion as contextual factors on idealized everyday- and formal physics problems. We show how some difficulties regarding conceptual understanding and factors influencing students' abilities to apply physics concepts in different contexts, can be implemented to enhance tuition.

Research questions

The main question this research attempted to answer was: To what extent are first-year university physics students able to apply formal conceptual reasoning to theoretical idealized situations set in different contexts? The following secondary questions were asked to obtain realistic, reliable and valid answers:

- (1) What information regarding students' epistemological beliefs and conceptual understanding is revealed by the changes in the direction and plane of motion in physics problems?
- (2) How can the acquired information be implemented in tuition to develop formal conceptual understanding?

METHOD

Research design

The chosen methodology was an explanatory sequential mixed-method design. The quantitative phase was completed by 418 students enrolled for first-year physics at a university in South Africa. The sample represented students from the calculus-based and non-calculus-based physics modules, as well as both genders. The number of students enrolled for the different modules is presented in Table 1. For the qualitative phase of the study four randomly selected students were interviewed individually in semi-structured interviews.

Data collection and processing

The research instrument for the quantitative phase was a multiple-choice questionnaire consisting of theoretical, idealized isomorphic problem pairs testing for the same underlying concept. The concept of free fall in idealized contexts — i.e. in the absence of air resistance and friction all objects have equal acceleration regardless of their mass — was the underlying concept in the questions on which this paper reports. The motion of two objects of unequal mass released at the same time and travelling the same distances, had to be considered. The motion had to be compared either in terms of the time the objects took to reach their destination or in terms of their final or initial velocities. The questionnaire comprised 21 problems. The four example problems discussed in this paper were all set in a formal conceptual context, but with different planes or directions of motion (Refer to Table 2). Student responses to questions 1 and 2 — settings with which the students were most familiar — were compared to their responses to questions in which the direction or the plane of motion was changed. The questionnaire was mostly self-complied with question 1 adapted from the Force Concept Inventory (Hestenes, Wells & Swackhamer, 1992) and question 4 adapted from the The Energy and Momentum Concepts Survey (Singh & Rosengrant, 2003). All the problems had an option which indicated the alternative conception that heavy objects fall faster. The percentages of correct as well as alternative answers are also presented in Table 2.

The inferential statistics for the questionnaire were obtained by using SPSS Statistics Version 22, Release 22.0.0. Cronbach's Alpha and the mean inter-item correlation were calculated to indicate the reliability of the research instrument. Two-way frequency tables of paired problems were used to determine the McNemar test statistic — effect size — and phi-coefficient for the paired problems. The results of the test statistics of the paired problems are presented in Table 3.

Open-ended questions used during the interviews allowed verbal analysis, enabled the interviewer to probe the students for self-explanations. The interviews were videotaped, transcribed and analysed for patterns and trends in the data.

RESULTS

The Cronbach's Alpha and the mean inter-item correlations for the questionnaire were 0.726 and 0.158 respectively, both indicating satisfactory degrees of reliability.

The number of students and the modules they were enrolled for, are presented in Table 1 below.

Table 1. Number of students in different physics courses

Physics module	N	BEng	BSc
FSKS 111 calculus based	226	66	160
FSKS 113 non-calculus based	255	1	254
Total number:	481	67	414

The four illustrative problems reported on in this paper are presented in Table 2. The table shows the percentage of students who chose the correct answer of the two objects travelling the same time or having the same final/initial speed, as well as the percentage of students who selected the option that illustrated the alternative conception.

Table 2. Reported questions and percentages of answers

Two metal balls (blocks) are the same size but one weighs twice as much as the other.	% correct	% alt conception
The balls are dropped from the roof of a single story building at the same instant in time.		
Question 1: $F \downarrow t$ Which ball will reach the ground first?	84	15
Question 2: $F \downarrow v$		
Which ball will reach the ground with the largest velocity?	69	25
Question 3: $F \uparrow v$		
The balls are projected upwards from the ground to reach the roof of a single story building at the same time. How do their initial velocities relate?	35	52
Question 4: $F \swarrow v$		
The blocks slide down two identical frictionless slides of similar height. Which one has the larger speed at the bottom of the slide?	29	48

Key: F = formal conceptual question; $\downarrow$ = vertical downward motion; $\uparrow$ = vertical upward motion; $\swarrow$ = motion on inclined plane; t = time; v = velocity/speed.

Table 3. Test statistics of paired-questions

Context	Paired items	ω	phi-coefficient Φ
$F \downarrow t : F \downarrow v$	1; 2	0.35	0.517
$F \downarrow t : F \uparrow v$	1; 3	0.65	0.118
$F \downarrow t : F \swarrow v$	1; 4	0.72	0.192
$F \downarrow v : F \uparrow v$	2; 3	0.48	0.132
$F \downarrow v : F \swarrow v$	2; 4	0.58	0.192
$F \uparrow v : F \swarrow v$	3; 4	0.10	0.222

DISCUSSION OF RESULTS

Students' epistemic beliefs and alternative conceptions

The percentages of students' selections of the different options are consistent with former research reporting the persistence of alternative (experiential) conceptions (Duit et al., 2014, Ledermann & Ledermann, 2014) in particular that heavy objects fall faster. For the three questions compared to question 1, a decline in the percentage of the correct answer concurred with an increase in the percentage of the alternative conception. This inverse relation can realistically be attributed to the difficulty students have in accepting the Newtonian principle for objects in free fall, namely acceleration equating net force/mass ratio. This attribution is founded on information obtained during the interviews that most students were uncertain whether the magnitude of the force of gravity or the gravitational acceleration was equal for

all falling objects. All the interviewed students expressed the opinion at some time, that the force of gravity exerted by the earth was equal for all objects.

Simplification

Physics thinking originates from reconstructing certain aspects under theoretical perspective (Duit et al., 2014). However, the large effect sizes present evidence that students found it significantly difficult to apply formal reasoning to problems without friction and the absence of air resistance, set in upward and inclined motion. Most students did not see disregarding friction or air resistance as simplification of the problems. The remark "It is confusing if friction and air resistance have to be ignored" summed up the general belief.

Effect of direction and plane of motion

The large effect sizes ($w = 0.72$ for questions 1 and 4, and $w = 0.58$ for questions 2 and 4) confirm that students used different knowledge frameworks to answer questions about vertical downward motion and motion on an inclined plane regardless of the physics variable that was considered. These effect sizes illuminate that the students' epistemological beliefs affect their conceptual understanding. From the effect sizes it is clear that motion on inclined planes revealed lack of conceptual understanding more than did motion in upward direction.

The large effect size for questions 1 and 3 ($w = 0.65$) suggested that students did not apply the same principle for an object moving in opposite vertical directions. This suggestion was confirmed by the reasons students gave for selecting their options during the interviews, e.g. "Up and downward motion are not the same. They are not subjected to the same principles". The very small effect size of questions 3 and 4 ($w = 0.10$) confirmed that students' responses to questions on vertical upward and inclined plane motion did not differ much, although the moderate phi coefficient ($\Phi = 0.222$) indicates that the students did not relate the said questions in the way they did questions 1 and 2 ($\Phi = 0.517$). These effect sizes provide evidence for the students' intuitive (epistemological) beliefs that physics knowledge is not coherent but consists of loosely connected conceptions.

Comparison between questions where not only the direction but also the physics variable differed, questions 1 and 3, demonstrated that the combination of changing both the direction of motion and the physics variable, resulted in a larger effect size than did changing only direction of motion with the same physics variable to be considered (question 2 and 3, $w = 0.48$). The effect size $w = 0.35$ for questions 1 and 2, illustrated the moderate effect that changing only the physics variable had on students' responses, whereas the large phi coefficient for these two questions proves that similar knowledge frameworks were applied for questions concerning motion in the same direction.

CONCLUSION

We conclude by answering the research questions:

- (1) What information regarding students' epistemological beliefs and conceptual understanding is revealed by the changes in the direction and plane of motion in physics problems?

This study confirms research reporting that students' epistemological beliefs regarding physics concept and phenomena are firmly rooted in their experiential knowledge and that it severely contradicts physics concepts (Duit et al., 2014). The negative influence of students' epistemological beliefs on their ability to transfer conceptual knowledge to unfamiliar situations is shown by the changes in the direction of plane of motion. Our results identify students' lack of understanding of how the complexity of natural phenomena is reduced by idealized theoretical perspectives, as a major factor contributing to their difficulty to apply

concepts and principles to explain phenomena and solve problems to make sense of the natural world (Duit et al., 2014; Ledermann & Ledermann, 2014).

- (2) How can the acquired information be implemented in tuition to develop formal conceptual understanding?

The results of our study offer a technique that not only reveals students' epistemological beliefs but also a surprisingly simple but effective way to determine whether students understand the concept of free fall, during tuition. By only reversing the direction of motion in questions commonly asked before instruction, existing alternative conceptions can be identified and addressed. Although students' difficulties to develop conceptual understanding and apply their formal conceptual knowledge to unfamiliar situations had been recognized ever since initial research on physics education was published, no former studies illustrated how these difficulties can be applied to aid instruction.

Finally, our study introduces a new approach: to reconsider the possibilities offered by documented difficulties in or limitations of instruction to develop conceptual understanding by turning them into guidelines for developing effective and relevant tuition tools.

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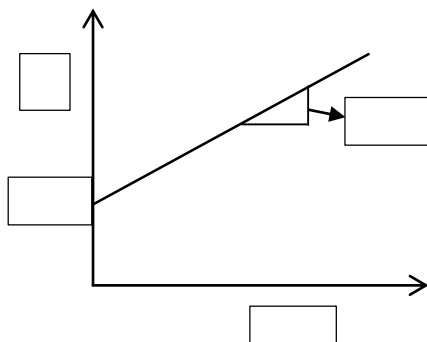
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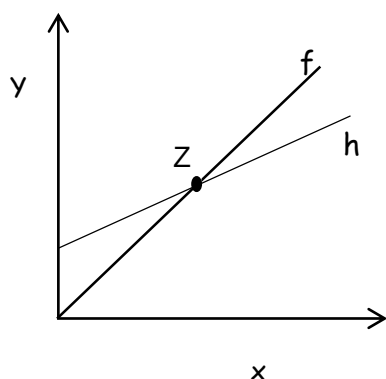
APPENDIX B: SECOND ITERATION - FIRST PRE-INSTRUCTION QUESTIONNAIRE

Section A: Mathematics

1. The equation: $y = 3x + 5$ is represented by the straight line graph:
Complete the graph by placing the values and variables of the equation in the appropriate blocks.



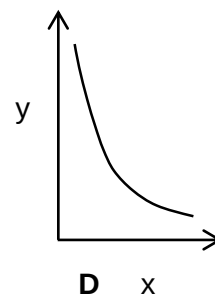
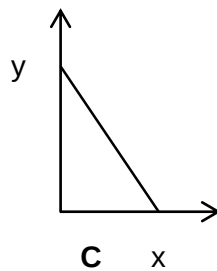
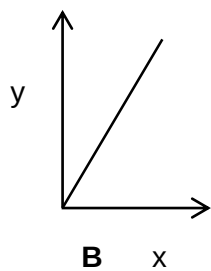
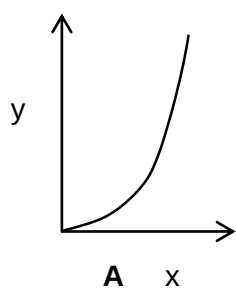
2. The functions f and h are represented on the graph below: f and h intersect at Z .



Which of the following statements regarding the gradients of the functions f and h , at point Z are correct in your opinion: (Tick the applicable block/s). Give a reason for your choice:

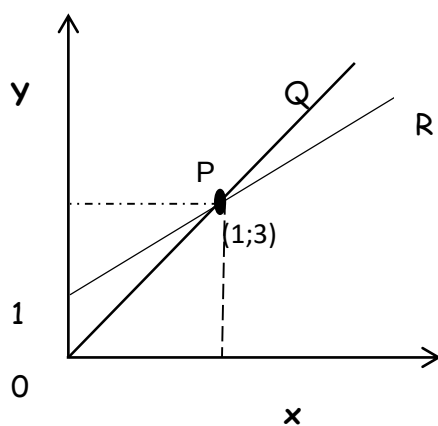
gradient $f >$ gradient h	Reason:
gradient $h >$ gradient f	
gradient $f =$ gradient h	

Pair each one of the given graphs with a corresponding equation in the table below.



Equation	Graph
$y = mx + c$	
$y = -mx + c$	
$y = \frac{1}{x}$	
$y = ax^2 + bx + c$	

3. Consider the two functions below:



3.1. Give the equation of function Q in the standard form: $y = mx + c$

3.2. Give the equation of function R in the standard form: $y = mx + c$

Section B

4. Consider the equations:

Equation P: $f(x) = ax^2 + bx$ and Equation Q: $\Delta x = v_i \Delta t + \frac{1}{2} a \Delta t^2$

4.1. Pair the variables in equation P with the corresponding variables in equation Q.

Variables: Equation P	Corresponding variable in equation Q
a	
x	
b	

4.2. What does variable a mean in equation P and what does variable a mean in equation Q?

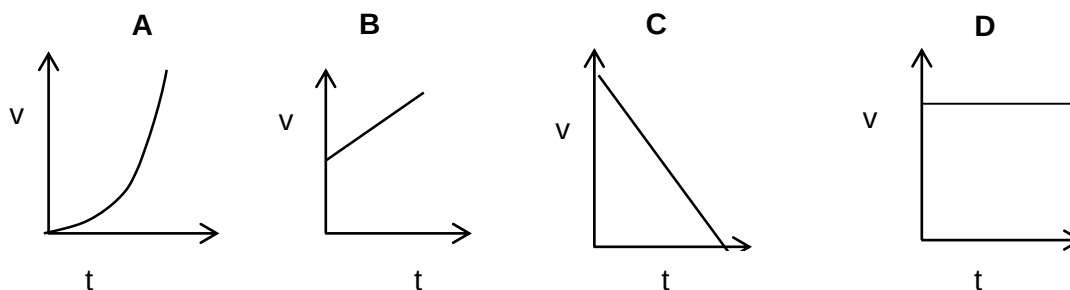
4.3. How does the meaning of variable x in equation P compare with the meaning of variable x in equation Q?

5. The following questions refer to the formula: $v_f = v_i + a \Delta t$ ($a = \text{constant}/0$)

5.1. Write the formula $v_f = v_i + a \Delta t$ in the standard mathematical form: $y = mx + c$.

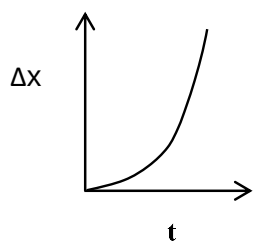
5.2. Circle the letters of all the graphs that are correct representations of the formula

$v_f = v_i + a \Delta t$:

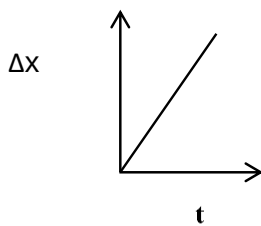


6. Consider the formula $\Delta x = v_i \Delta t + \frac{1}{2} a \Delta t^2$. Which graph(s) below will represent the formula under the following conditions:

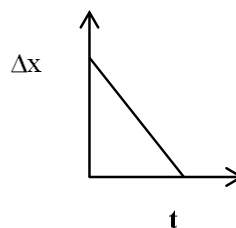
6.1. If $a = 0$



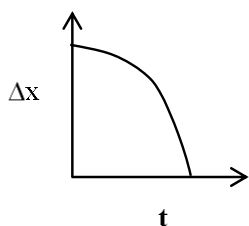
A



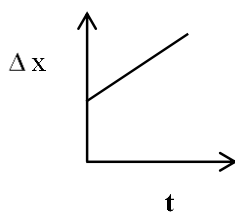
B



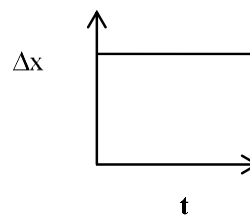
C



D



E



F

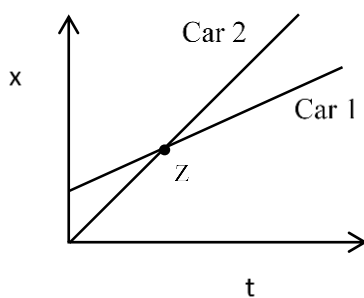
6.2.

If

$$a \neq 0$$

	Condition	Graph/s
6.1.	$a = 0$	
6.2.	$a \neq 0$	

7. The following position/time graph represents two cars driving at different velocities.

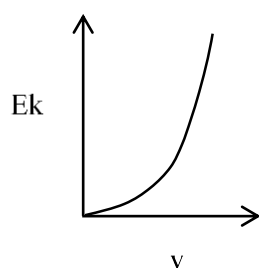


Which of the following statements regarding the velocity of the two cars at point Z are correct in your opinion? (Tick the applicable block). Give a reason for your choice:

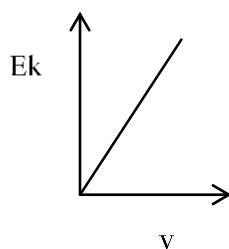
velocity car 1 > velocity car 2	
velocity car 2 > velocity car 1	
velocity car 1 = velocity car 2	

8. Circle the letter of all the graphs that, in your opinion, are representations of the given formulas. Assume that all variables remain constant except those represented in the graph. Please explain each of your choices.

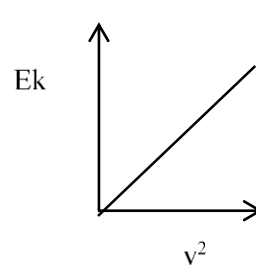
8.1. $E_k = \frac{1}{2}mv^2$



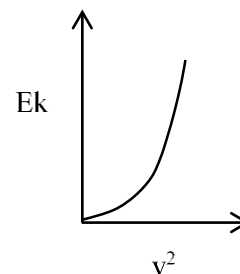
A



B

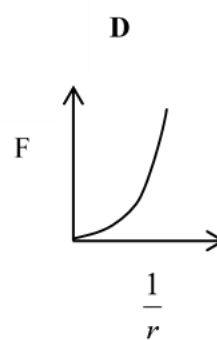
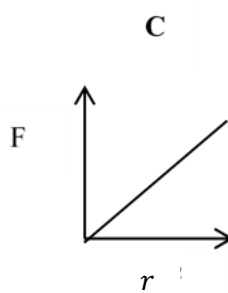
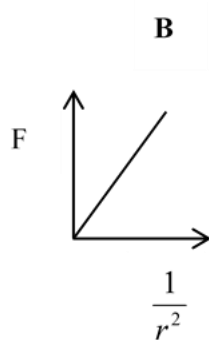
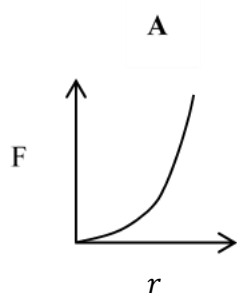


C



D

8.2. $F = k \frac{Q_1 Q_2}{r^2}$



APPENDIX C: SECOND ITERATION - WORKSHEETS

ACTIVITY 1: Experiential knowledge - Self-assessment

Answer the following three questions by using your experiential knowledge and intuition. At the end of the workbook, answer them again and check whether you have to revise your answers or not.

Answer the following questions according to your intuition.

1. A hockey player is hitting a ball with a hockey stick. The ball was initially at rest on the ground. While the stick is pushing the ball it experiences a constant force. The velocity of the ball.

- (a) increases for a short time and then remains constant.
- (b) increases all the time, but with smaller and smaller amounts.
- (c) increases with the same amount all the time.
- (d) remains constant all the time

Give a reason for your answer:

2. After hitting the hockey ball, it is released and rolls in a straight line on the smooth hockey field. The velocity of the ball after release will:

- (a) stay the same for some time and then decrease to zero
- (b) increase for some time and then decrease to zero
- (c) continuously decrease all the time until it stops
- (d) It depends on the velocity with which the ball has been hit.

Give a reason for your answer:

ACTIVITY 2: Experiencing the effect of a constant force

Context: Horizontal motion

Method

Hook the end of a rubber band to a trolley and its other end to a metre stick as shown in Figure 1-1 below. Stretch the rubber to a fixed amount (make a mark on the metre stick), so providing a constant force.

Hold the trolley and stretch the rubber by pushing on the metre stick so that the mark coincides with the front edge of the trolley. Now release the trolley and move forward with it, keeping the rubber stretched the same amount all the time. Try to keep up with the trolley (Figure 1-2).

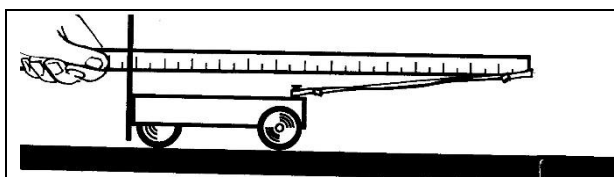


Figure 1-1: How to apply a constant force



Figure 1-2: Don't let the trolley run away with you

Now attach a ticker timer tape to the trolley and apply a constant force again. Carefully observe the change in spacing of the dots.

Observations:

While exerting a constant net force on the trolley, what do you observe about the velocity of the trolley?

When dots are made on a ticker tape, what do you observe about the spaces between the dots as the trolley moves from rest to the end?

Alternative conception addressed in activity 2

Alternative conception: Force is associated with velocity.

Scientific conception: The scientific conception implies that if the *mass* of an object remains constant, and the *net force* is constant, the *acceleration* is also constant but the *velocity* changes with time. The velocity can increase, decrease or change direction with time.

ACTIVITY 3: Motion on an inclined plane and free-fall

Aim:

To study the force-incline relationship for a trolley on inclined planes and in free-fall as a special case.

ACTIVITY 3.1: Qualitative experiment

Aim: Investigating the relationship between the “weight” of a trolley on an inclined plane and the angle of incline.

Method:

A trolley is rolled down incline planes of different angles. Hold your hand at the bottom of the ramp to use it as a qualitative force meter to “feel” the force exerted by the trolley. How would the angle of incline influence the force exerted by the trolley?

- Prediction: Predict what the outcome of the experiment will be. Give reasons for your prediction
- Observation: Do the experiment and write down your observation.
- Explanation: Explain the observation and compare it with your prediction. Find reasons for similarities or differences.

ACTIVITY 3.2.

Aim: To study the force-acceleration relationship for a trolley on inclined planes and in free-fall as a special case.

Method:

- Place a trolley on an inclined plane. Measure the angle of incline.
- Measure the distance that the trolley would travel.
- Release the trolley and measure the time that it travels the distance.
- Use a linear motion equation to calculate the acceleration of the trolley.
- Use the mass of the trolley and the angle of incline to calculate the component of the weight that causes the trolley to accelerate down the inclined plane.
- Repeat the experiment for two more angles of incline.
- Then repeat the experiment for a trolley in free fall (i.e. the angle of incline is 90°).

Results:

For the first run, show all your measurements and calculations:

- Calculate the angle of incline:

$$\tan \theta = \frac{\text{height}}{\text{adjacent}}$$

- Initial velocity: $v_i = 0 \text{ m/s}$

- Distance travelled along ramp: 1.03 m
- Mass of trolley: 0.62 kg

Mass trolley _____ kg			
Incline (°)			
Time (s)			
First run			
Second run			
Third run			
Average			

Time of travel along the ramp: _____

- Calculation of constant acceleration of trolley:

Angle of incline (°)	Distance (m)	Average time (s)	Acceleration (m.s ⁻²) ($\Delta y = v_i \Delta t + \frac{1}{2} a \Delta t^2$)

Calculation of component of weight along the plane:

(m= kg)	
Angle (°)	$F_{//g} = mg \sin \theta$

Summarize the results for different angles of incline:

Angle of incline	Distance (m)	Time (s)	Acceleration (m.s ⁻²)	Component of weight (N)
8.9°	1.03	1.10		
11.6°	1.03	0.81		
22.9°	1.03	0.59		
90.0°	1.03	0.45		

Draw of graph of force versus acceleration using the results of the table.

Apply Newton's second law of motion to calculate the mass of the trolley from the gradient of the graph.

Conclusions:

What do you conclude from the shape of the graph?

Evaluation of results:

Measure the mass of the trolley and explain possible differences between the mass obtained from the graph and from the measurement.

Use the equations $F_{net} = ma$ and $F_{//g} = mg \sin \theta$ to derive an equation that gives the acceleration along the incline in terms of the acceleration of gravity. Relate the equation to the concept of free fall.

Do different laws of motion apply to vertical free-fall motion and motion on horizontal or inclined planes? Explain your answer with reference to Newton's second law.

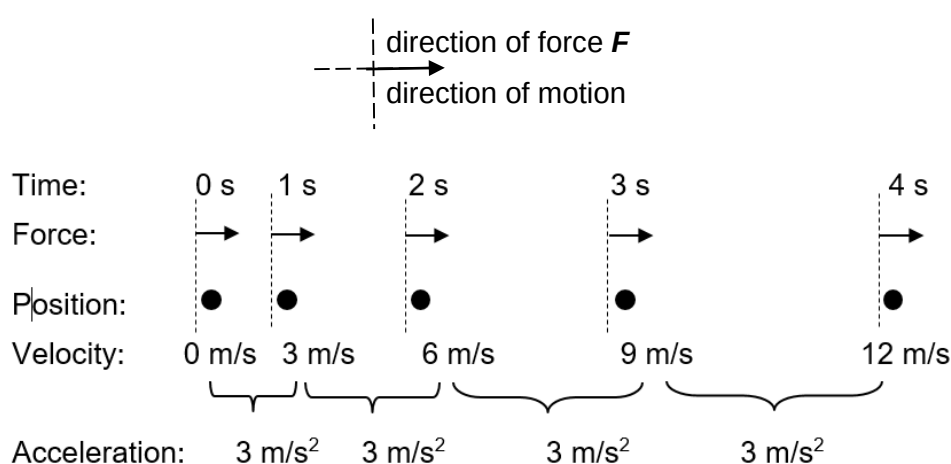
ACTIVITY 4: Using representations to show the association of a net force with positive and negative accelerations.

4.1. Acceleration in the same direction as the motion.

Example 1: Representation of $a = +3 \text{ m/s}^2$ (Horizontal motion)

Motion diagram:

Apply a constant force on a ball on a smooth horizontal surface (neglect friction). The force (F) acts in the direction of motion $\therefore$

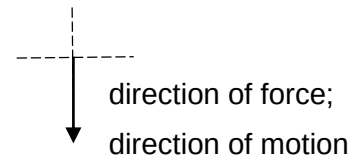


Example 2: Representation of $a = +g = 9.8 \text{ m.s}^{-2}$ (Vertical motion)

Motion diagram:

The earth applies a constant force on a ball in free fall (neglect friction). The force (**F**) acts in the direction of motion. Take downwards as the positive direction.

Time	Force	Position	Velocity	Acceleration
0 s	↓	●	0 m/s	
1 s	↓	●	9.8 m/s	9.8 m/s ²
2 s	↓	●	19.6 m/s	9.8 m/s ²
3 s	↓	●	29.4 m/s	9.8 m/s ²
4 s	↓	●	39.2 m/s	9.8 m/s ²

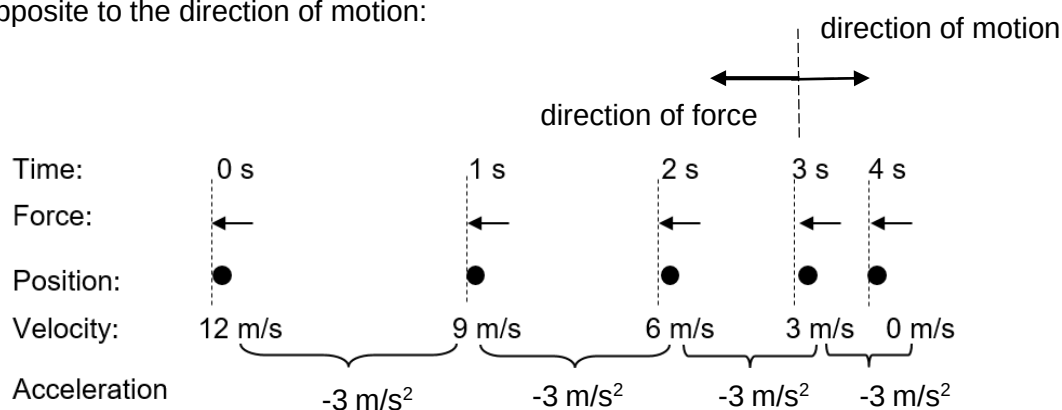


4.2. Acceleration in opposite direction as motion

Example 3: Representation of $a = -3 \text{ m/s}^2$

Motion diagram:

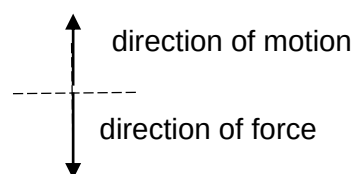
Apply a constant force on a ball on a smooth horizontal surface (neglect friction). The force acts opposite to the direction of motion:



Example 4: Representation of $a = -g = -9.8 \text{ m.s}^{-2}$

A ball is thrown upwards into the air. The earth applies a constant force on a ball thrown upwards (neglect air resistance). The force acts opposite to the direction of motion. Take upwards as positive.

Time	Force	Position	Velocity	Acceleration
4 s	↓	●	0 m/s	- 9.8 m.s ⁻²
3 s	↓	●	9.8 m/s	- 9.8 m.s ⁻²
2 s	↓	●	19.6 m/s	- 9.8 m.s ⁻²
1 s	↓	●	29.4 m/s	- 9.8 m.s ⁻²
0 s	↓	●	39.2 m/s	- 9.8 m.s ⁻²

**Conceptual application of the force-mass relation for constant acceleration**

Consider the following question:

Two balls of the same size are dropped from the same height. The mass of ball A is twice as large as the mass of ball B. Friction is neglected.

1. Which ball will reach the ground first?
2. Does ball A or ball B experience the larger gravitational force?
3. Which ball will obtain the larger velocity?
4. What incorrect answer do learners often give to this question?
5. What is the scientifically correct answer to this question?

Explain the correct answer by referring to the force-mass relation of Newton's second law.

ACTIVITY 5. Air resistance

- For the magnitude of the force due to air resistance f_a (in N) the following applies:

$$f_a = \frac{1}{2} c_f A \rho v^2$$

- In this formula c_f is the air resistance coefficient, A is the frontal area (in m^2), ρ is the density of air and v is the velocity (in m/s).

- The formula for the force due to air resistance may be simplified and written as:

$$f_a = k v^2$$

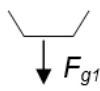
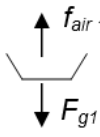
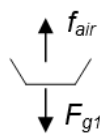
- Air resistance thus depends on the velocity of the moving object. This has important implications for falling objects. The velocity of an object falling near the surface of the earth increases due to the force of gravity (magnitude F_g).
- If air resistance is neglected, the object will keep on accelerating with $g = 9.8 \text{ m/s}^2$, i.e. its velocity will increase with 9.8 m/s every second.
- If air resistance is taken into account, this resistive force will increase with the increase in velocity of the falling object. The velocity of the object will increase slower and slower until at last a constant velocity is reached.
- The velocity and air resistance can only increase to the point where the two forces balance, i.e. where their magnitudes are equal, i.e. of $F_g = f_a$. From that point onwards the air resistance and the velocity of the object remains constant as it keeps on falling to the ground. This is called the terminal velocity of the object.
- The resultant of the two forces F_g and f_a is the resultant force F_{res} that causes the acceleration and an increase in velocity:
$$F_{\text{net}} = m a$$
- The resultant force is equal to the vector sum of the forces. Note that the force due to air resistance has as a negative value, because the force opposes the motion.

- **Explanation of different effects of air resistance on different objects**

- (a) Drop an open and a fumbled cake cup from the same height. Which one reaches the ground first?

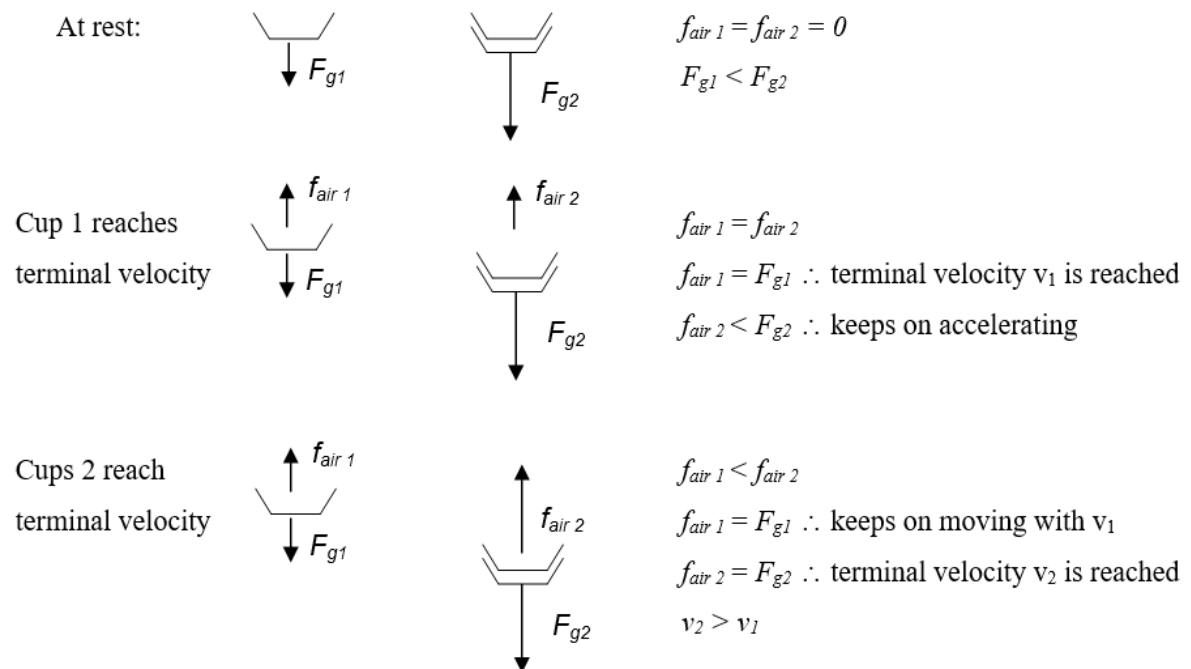
The fumbled cup reaches the ground first

Explanation:

At rest:			$f_{air\ 1} = f_{air\ 2} = 0$ $F_{g1} = F_{g2}$
Cup 1 reaches terminal velocity			$f_{air\ 1} > f_{air\ 2}$ $f_{air1} = F_{g1} \therefore$ terminal velocity v_1 is reached $f_{air\ 2} < F_{g2} \therefore$ keeps on accelerating
Cups 2 reach terminal velocity			$f_{air\ 1} < f_{air\ 2}$ $f_{air\ 1} = F_{g1} \therefore$ keeps on moving with v_1 $f_{air2} = F_{g2} \therefore$ terminal velocity v_2 is reached $v_2 > v_1$

- (b) Drop one and two cake cups from the same height. Which one reaches the ground first?
The two cups placed into one another reaches the ground first.

Explanation:



APPENDIX D: SECOND ITERATION - SECOND PRE-INSTRUCTION QUESTIONNAIRE

Q1. Two metal balls are the same size but one weighs twice as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. Air resistance must be neglected.

Which ball will reach the ground first?

1. The heavier ball.
2. The lighter ball.
3. Both will reach the ground simultaneously.
4. Not enough information is provided.

Q2. Which ball in Question 1 will reach the ground with the largest speed?

1. Both will reach the ground with the same speed.
2. Not enough information is provided.
3. The heavier ball.
4. The lighter ball.

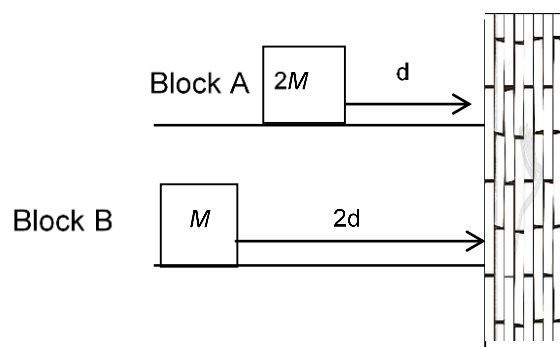
Q3. A heavily loaded truck, and a motorcar travel side by side on a highway. The mass of the truck is double that of the car. The drivers notice the changing traffic light and start to apply the brakes at the same time and come to a halt at the traffic light simultaneously. Which statement below is true for the force applied by the brakes? Ignore the effect of friction.

1. $F_{\text{truck}} = 2 F_{\text{motorcar}}$
2. $F_{\text{truck}} = \frac{1}{2} F_{\text{motorcar}}$
3. $F_{\text{truck}} = F_{\text{motorcar}}$

Q4. Which statement below is true for the accelerations experienced by the vehicles in Question 3?

1. $a_{\text{truck}} = 2 a_{\text{motorcar}}$
2. $a_{\text{truck}} = \frac{1}{2} a_{\text{motorcar}}$
3. $a_{\text{truck}} = a_{\text{motorcar}}$

Q5. Two blocks with different mass are simultaneously pulled from rest along a horizontal plane with identical constant accelerations. Block A has twice the mass of B but travels half the distance of block B. Which one will reach the wall first? Ignore the effect of friction.



1. Block A.
2. Block B.

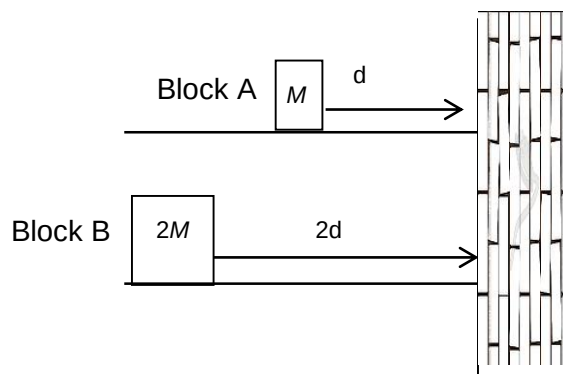
3. Both will reach the wall at the same time because they travel the distance d together.
4. Both will reach the wall simultaneously because B travels a longer distance and reaches a larger speed.

Q6. While in a playground you and your 10-year-old niece slide down two frictionless slides of similar height. Your mass is three times that of your niece. Assuming that both of you begin sliding from rest, which one of the following statements best describes who has a larger speed at the bottom of the slide? Ignore the effect of friction and air resistance.

1. You because your larger weight causes a greater downward acceleration.
2. Your niece because lighter objects are easier to accelerate.
3. Both of you will have the same speed at the bottom.

Q7. Two blocks, A (mass M) and B (mass $2M$), are simultaneously accelerated from rest over different distances. The force on block B is twice the force on block A and the distance over which B is accelerated is twice that of block A. Ignore the effect of friction.

Which block will reach the wall first?



1. Block B because it reaches a larger speed.
2. Both will reach the wall simultaneously because they travel the distance d together.
3. Both will reach the wall simultaneously because B travels a longer distance and reaches a larger speed.
4. Block A because it travels a shorter distance.

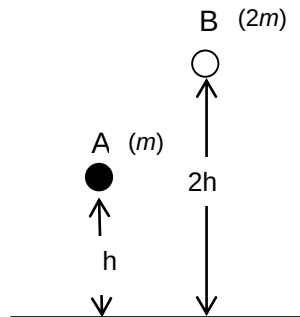
Q8. Consider two metal balls that are the same size, one weighing twice as much as the other. These balls are thrown upwards from the ground and reach the roof of a single story building at the same time. Ignore the effect of air resistance.

Which statement is true about their initial velocities?

1. The heavier ball must have the larger initial velocity.
2. The lighter ball must have the larger initial velocity.
3. Both are projected with the same initial velocity.

- Q9. Two metal balls are dropped simultaneously from different heights. Ball A (m) has half the mass of ball B ($2m$) but falls half the distance (h) to the ground. Ignore the effect of air resistance.

Which ball will reach the ground first?



1. Ball A.
 2. Ball B.
 3. Both will reach the ground simultaneously.
 4. Not enough information is provided.
- Q10. Which statement is true for the speed of the balls in Question 9?
1. The balls will reach the ground with the same speed.
 2. Ball A will have the larger speed.
 3. Ball B will have the larger speed
 4. You need to do a calculation to get an answer.

APPENDIX E: SECOND ITERATION - IMPLEMENTING MOTION DIAGRAMS

PVRI approach

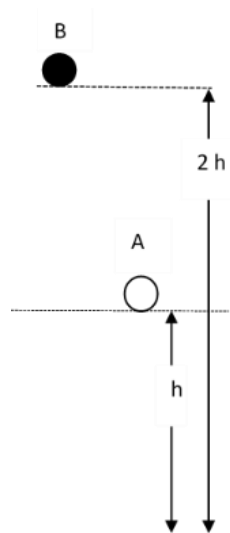
i) Predict ii) Visualize the invisible using pictorial representations; motion diagrams iii) Reconcile (Qualitative conceptual reasoning using equations) iv) Infer (generalize)

1. Example 1:

1.1. Prediction from verbal representation:

Two metal balls of the same sizes are dropped simultaneously from different heights. Ball A has half the mass of ball B but falls half the distance to the ground. Ignore the effect of air resistance. Which ball will reach the ground first?

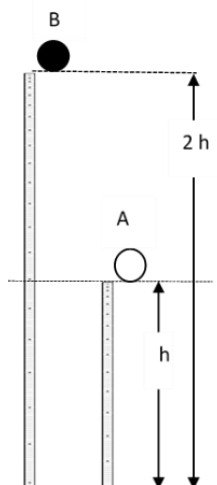
1.2. Unpack the problem: Pictorial representation



When released - both A and B - initial velocity is zero; acceleration = g .

1.3. Visualize the invisible “Observation” using motion diagram:

Condition: Ignore the effect of air resistance $\therefore$ equal acceleration $\therefore$ motion diagrams identical



1.4. Questions guiding reasoning:

- i) How long does it take ball A to reach the ground?
(14 time intervals)
- ii) How far does ball B travel in the same time?
(14 time intervals - to fall through h and reach the point where A was.)
- iii) Which ball will hit the ground first? Explain.
(Since they started with equal initial velocities and moved with equal acceleration, they both fell through (h) in the same time. While A will have reached the ground ball B will only have reached the height from which A was released and still has to cover another height h to reach the ground).
- iv) How long does it take ball B to reach the ground?
(Counting the time interval B needs to reach the ground: $14 + 6 = 20$).
- v) Why is the travelling time for ball B not double the time of ball A?

1.5. Qualitative reasoning: Equations (“Explain” – Reconciling interpretation of motion diagram with prediction)

Qualitative reasoning: compare the time to reach the ground $y = v_i \Delta t + \frac{1}{2} a \Delta t^2$

Physics quantities	y	v_i	a	Δt
Ball A	y	0	g	?
Ball B	$2y$	0	g	?

If both start from rest and accelerate at the same rate it is logical that the one travelling the larger distance will take the longer time.

1.6. Validation of conceptual reasoning: Equations - comparative mathematical reasoning.

Ball A:

$$y = v_i \Delta t + \frac{1}{2} a \Delta t_A^2$$

$$y = 0 + \frac{1}{2} a \Delta t_A^2$$

$$\Delta t_A^2 = \frac{2y}{a}$$

$$\Delta t_A = \sqrt{\frac{2y}{a}}$$

Ball B:

$$2y = v_i \Delta t + \frac{1}{2} a \Delta t_B^2$$

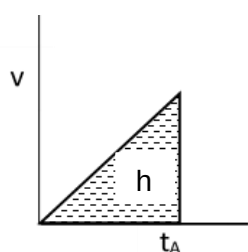
$$2y = 0 + \frac{1}{2} a \Delta t_B^2$$

$$\Delta t_B^2 = 2 \frac{2y}{a}$$

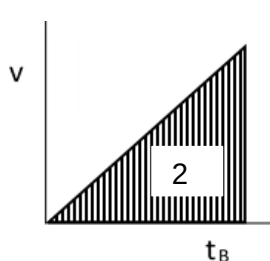
$$\Delta t_B = \sqrt{2} \sqrt{\frac{2y}{a}}$$

1.7. Graphs: Transition between multiple representations

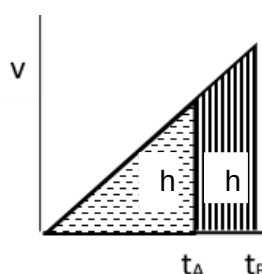
Velocity versus time graphs for balls falling from rest



Ball A



Ball B



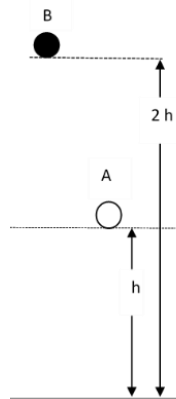
Graphs on same axis

2. Example 2:

2.1. Prediction from verbal representation

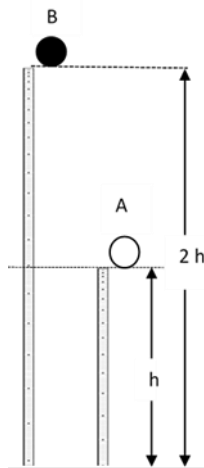
Two balls A and B (with the **same/different mass**) are dropped from different heights and at different times. The initial height of ball A is twice that of ball B. Ball A is released first. Ball B is released at the exact moment that ball A passes ball B at height h . Ignore the effect of air resistance. Which ball will reach the ground first?

2.2. Unpack the problem: Pictorial representation



(If $m_B > m_A$ and air resistance is ignored, the mass has no effect on acceleration because the F_g/m ratio is the same).

1.3. Visualize the invisible “Observation” - Motion diagram:



2.4. Questions guiding reasoning

- What distance do the balls travel together? (h)
- What are the initial velocities of the respective balls for that distance?
- How do the times to cover that distance compare?

2.5. Qualitative reasoning: Equations (“Explain” – Reconciling interpretation of motion diagram with prediction)

$$\Delta y = v_i \Delta t + \frac{1}{2} a \Delta t^2$$

Physics quantities	Δy	v_i	a	Δt
Ball A	Δy	0	g	?
Ball B	Δy	v_i	g	?

$$\Delta y = v_i \Delta t + \frac{1}{2} a \Delta t^2$$

For ball A, falling from rest ($v_i \Delta t = 0$.) y is determined by one term: $\frac{1}{2} a \Delta t_A^2$

For ball B, Δy is determined by two terms: $v_i \Delta t_B + \frac{1}{2} a \Delta t_B^2$

But $\Delta y_A = \Delta y_B$ therefore $\frac{1}{2} a \Delta t_A^2 = v_i \Delta t_B + \frac{1}{2} a \Delta t_B^2 \therefore \Delta t_A > \Delta t_B$

2.6. Validation of conceptual reasoning: Equations - comparative mathematical reasoning.

For ball A:

$$\Delta y = v_i \Delta t_A + \frac{1}{2} a \Delta t_A^2$$

$$\Delta y = 0 + \frac{1}{2} a \Delta t_A^2$$

$$\frac{1}{2} a \Delta t_A^2 = \Delta y$$

$$\Delta t_A^2 = \frac{2\Delta y}{a}$$

$\therefore$ time for B is less than time for A

For ball B:

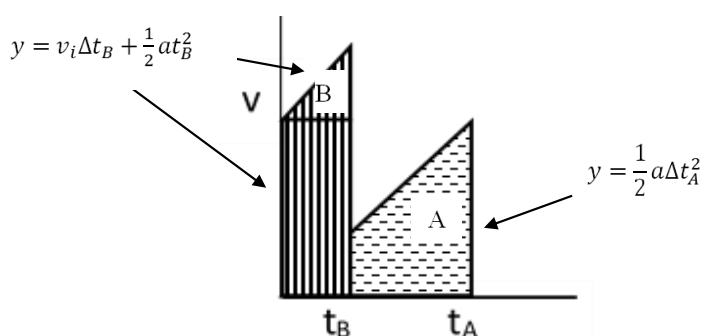
$$\Delta y = v_i \Delta t_B + \frac{1}{2} a \Delta t_B^2$$

$$\Delta t_B^2 = \frac{2(\Delta y - v_i \Delta t_B)}{a}$$

$$\frac{1}{2} a \Delta t_B^2 = \Delta y - v_i \Delta t_B$$

$$\Delta t_B^2 = \frac{2\Delta y}{a} - \frac{2(v_i \Delta t_B)}{a}$$

2.7. Graphs: Transition between multiple representations



Area A = area B = height h ; because of $v_{iB} \neq 0$; B will fall through height h in a shorter time.

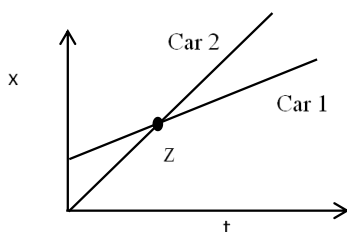
APPENDIX F: SECOND ITERATION - POST-INSTRUCTION

QUESTIONNAIRE

Instructions to students:

- A. Please explain all your answers as you would explain it to learners in your class, using any kind of physics tools, e.g. equations, motion -, vector- or force diagrams, to assist your explanation.
- B. Do not go back to questions you have already answered.

1. The following **position/time** graph represents two cars driving at different velocities in the same direction.

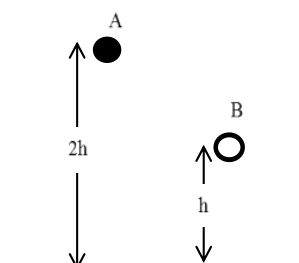


Which of the following statements regarding the velocity of the two cars at point Z are correct in your opinion? (Tick the applicable block). Give a reason for your choice:

a. $v_{\text{car 1}} > v_{\text{car 2}}$	
b. $v_{\text{car 2}} > v_{\text{car 1}}$	
c. $v_{\text{car 1}} = v_{\text{car 2}}$	

2. Two balls A and B with different mass are at the same time dropped from different heights. The mass of ball A is twice that of ball B. Ignore the effect of air resistance.

Which ball will reach the ground first?



- a. Ball A,
- b. Ball B,
- c. Both will reach the ground simultaneously.

Please explain your answer as you would to learners.

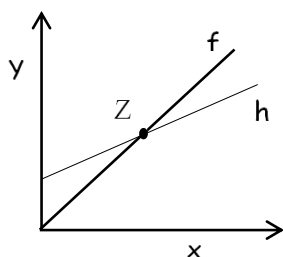
3. A heavy loaded truck, and a motorcar travel side by side on a highway. The mass of the truck is double that of the car. The drivers notice the changing traffic light and start to apply the brakes at the same time and come to a halt at the traffic light simultaneously.

Which statement below is true for the accelerations experienced by the vehicles and the force applied by the brakes? Choose one answer in each column. Please explain your answer.

Acceleration:	Force
a. $a_{\text{truck}} = 2 a_{\text{motorcar}}$	d. $F_{\text{truck}} = 2 F_{\text{motorcar}}$
b. $a_{\text{truck}} = \frac{1}{2} a_{\text{motorcar}}$	e. $F_{\text{truck}} = \frac{1}{2} F_{\text{motorcar}}$
c. $a_{\text{truck}} = a_{\text{motorcar}}$	f. $F_{\text{truck}} = F_{\text{motorcar}}$

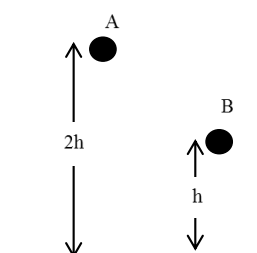
4. The functions f and h are represented on the graph below: f and h intersect at Z .

Which of the following statements regarding the gradients/slopes of the functions f and h , at point Z are correct in your opinion? Give a reason for your answer.



a. $m_f > m_h$
b. $m_h > m_f$
c. $m_f = m_h$

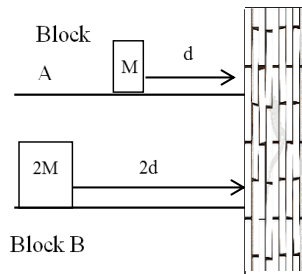
5. Two balls A and B with the **same mass** are dropped from different heights and at different times. The initial height of ball A is twice that of ball B. Ball A is released first. Ball B is released at the exact moment that ball A passes ball B at height h . **Ignore the effect of air resistance.** Which ball will reach the ground first?



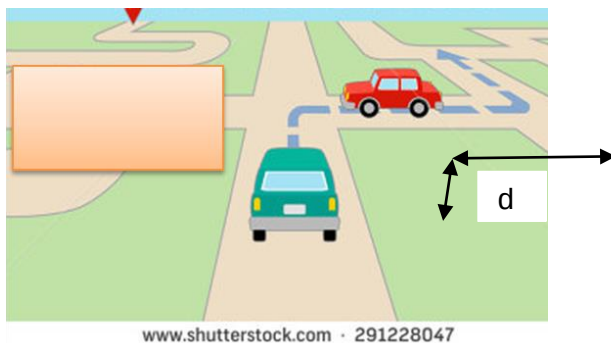
- Ball A,
- Ball B,
- Both will reach the ground simultaneously

Please explain your answer.

6. Two blocks, A (mass M) and B (mass $2M$), are accelerated over different distances. The force on block B is twice the force on block A and the distance over which B is accelerated is twice that of block A. Block B is moved first. Block A is moved at the exact moment that block B passes block A at distance d . Friction can be neglected. Which block will reach the wall first?



- Both will reach the wall simultaneously.
 - Block A
 - Block B
7. A small car and a heavy motor vehicle travelling at the same speed approach a crossing with no stop signs, (i.e. at a 90° angle). When they are both distance d from the crossing, each driver decides to give way to the other and applies the brakes, resulting in the two vehicles coming to rest at the crossing at the same time.



- Use an appropriate physics equation of motion to compare their accelerations.
- Compare the braking force of the vehicles.

Please explain your answers as you would to learners.

APPENDIX G: THIRD ITERATION - PRE-(DIAGNOSTIC)

QUESTIONNAIRE

Questionnaire: 3 rd year B.Ed. students	
Question	Options
1. Two balls are the same size but the mass of one is three times as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. Ignore the effect of air resistance. The time it takes the balls to reach the ground below will be:	1. Longer for the heavier ball. 2. Three times as long for the lighter ball as for the heavier one. 3. Longer for the lighter ball, but not three times as long as for the heavier ball. 4. The same time for both balls.
2. Two balls are the same size but have different mass. The two balls are placed at the top of an incline (ramp) and start to move downwards along the smooth, inclined plane, from rest at the same time. Ignore the effect of air resistance and friction. The time it takes the balls to reach the ground below will be:	1. Less for the lighter ball. 2. Less for the heavier ball. 3. Both will reach the ground at the same time. 4. Impossible to say, the angle of incline must be known. 5. Impossible to say, the ratio of the masses must be known.
3. Consider two metal balls that are the same size, but the mass of one is twice as much as the other. These balls are thrown upwards from the ground and reach the roof of a single story building at the same time. Ignore the effect of air resistance. Which statement is true about their initial velocities?	1. Both balls must be projected with the same initial velocity. 2. The heavier ball must have double the initial velocity of the lighter one. 3. The heavier ball must have a larger initial velocity than the lighter ball, but not double as much. 4. The lighter ball must have double the initial velocity of the heavier ball. 5. The lighter ball must have a larger initial velocity than the heavier ball, but not double as much.
4. Two balls are the same size but have different mass. The two balls are rolled upwards from the bottom of inclined planes (ramp), with the same initial velocity and reach their respective maximum heights at the same time. Ignore the effect of air resistance and friction. The distances the balls travel on the inclines are:	1. Less for the lighter ball. 2. Less for the heavier ball. 3. Both will travel the same distance. 4. Impossible to say, the angles of incline must be known. 5. Impossible to say, the ratio of the masses must be known.
5. A rubber play-ball and a bowling ball are released simultaneously from the same	1. Double for the rubber ball than for the bowling ball.

Questionnaire: 3 rd year B.Ed. students	
height. The mass of the rubber ball is half that of the bowling ball. Ignore the effect of air resistance. The downward force experienced by the balls will be:	2. Double for the bowling ball than for the rubber ball. 3. Less for the rubber ball, but not half that of the bowling ball. 4. Less for the bowling ball, but not half that of the rubber ball. 5. The same magnitude of force for both balls.
6. Two balls are the same size but the mass of one is three times as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. The effect of air resistance must be ignored. The force acting on the balls will be:	1. Three times as much for the heavier ball as for the lighter one. 2. More for the heavier ball, but not three times as much as the lighter ball. 3. Three times as more for the lighter ball as for the heavier one. 4. More for the lighter ball, but not three times as much as the heavier ball. 5. The same force for both balls.
7. Consider two metal balls that are the same size, but the mass of one is twice as much as the other. These balls are thrown upwards from the ground and reach the roof of a single story building at the same time. Ignore the effect of air resistance. Which statement is true about the force acting on the balls while they are in the air?	1. Both balls experience the same initial force. 2. The heavier ball must have double the force of the lighter one. 3. The heavier ball must have a larger force than the lighter ball, but not double as much. 4. The lighter ball must have double the force of the heavier ball. 5. The lighter ball must have a larger force than the heavier ball, but not double as much.

APPENDIX H: THIRD ITERATION - WORKSHEETS

Investigating factors that influence the acceleration of objects moving on inclined planes:

- i) Angle of incline
- ii) Mass of object

ACTIVITY 1:

- i) A metal ball is rolled down incline planes of different angles. How does the angle of incline influence the force exerted by the ball?
 - ii) A heavy ball and a lighter ball are rolled down inclined planes; which ball will exert the bigger force when it hits your hand?
- 1.1. Prediction: Give reasons for your prediction
 - 1.2. Variables: Identify the i) independent variable ii) dependent variable and iii) variables that are kept constant during the experiment.
 - 1.3. Results: Observation
 - 1.4. Explanation Compare the prediction and observation
 - 1.5. Questions: What does the force that the ball exerts represent?

Why should the surfaces of the inclined plane as well as those of the balls be very smooth?

ACTIVITY 2

- i) How does the angle of an inclined plane effect the time it takes for a ball to travel down the plane?
 - ii) What influence does the mass of a ball have on the time it takes to travel down an inclined plane?
- 2.1. Prediction: Give reasons for your prediction
 - 2.2. Variables:

Independent variable (What did you change?)	Dependent variable (What did you measure?)	Constant variable (What did you keep the same?)
i)	i)	i)
ii)	ii)	ii)

- 2.3. Results: Observation
 - 2.3.1. Initial velocity of the ball:
 - 2.3.2. Distance travelled along ramp:

2.3.3. Table 1: RESULTS FOR ACTIVITY 2

Mass ball 1:			Mass ball 2:		
Incline (°)	θ_1		θ_2		θ_3
Time (s)	Ball 1	Ball 2	Ball 1	Ball 2	Ball 1
First run					
Average					

2.4. Explanation: interpretation of results and compare with prediction

Table 2: Acceleration of balls on different inclines

Angle of incline (°)	Distance (m)	Average Time (s)		Acceleration (m.s^{-2}) ($\Delta y = v_i \Delta t + \frac{1}{2} a \Delta t^2$).	
		Ball 1	Ball 2	Ball 1	Ball 2
θ_1					

2.4.1. With which measurement can the acceleration of the ball be related? Explain.

2.4.2. How does the acceleration of the different balls compare at the same incline?

2.4.3. Did the observation confirm your prediction? Explain.

2.4.4. What precautions are taken to minimize the effect of friction and air resistance?

ACTIVITY 3:

Free– body diagrams of objects on inclined planes and net forces

3.1. Draw complete, labelled free-body diagrams for each ball for each of the angles of incline as noted in the table in 2.3.1. The diagrams must contain the perpendicular components of the forces of gravity.

3.2. Using the same diagrams, indicate how the absence of friction will alter the diagram.

Angle of incline(°)	Force diagram ball 1	Force diagram with no friction
θ_1		

3.3. Write down a generic equation (in symbolic form) that can be used to calculate the component of the force of gravity that causes the ball/s to accelerate down the inclined planes.

3.4. Write an equation for the net force in terms of the sum of forces as well as in terms of the mass and acceleration.

3.5. How does the absence of friction change the way the equation in 3.4 is written?

- 3.6. Complete the table below by calculating the magnitude of the force causing the acceleration along the inclined plane for each ball and for each angle.

Table 3: Component of the force of gravity along the incline

	$F_{lg} = mgsin\theta$	
Angle ($^{\circ}$)	Ball 1 (m= kg)	Ball 2 (m= kg)
θ_1		

ACTIVITY 4:

Determine the relationship between the net force on and the acceleration of the balls.

Determine the net force on each ball at each incline, using the equation for Newton's second law and the results in Table 2.

Table 4: Net force along the incline

	a (m/s ²)		$F_{net} = ma$	
Angle ($^{\circ}$)	Ball 1	Ball 2	Ball 1 (m= kg)	Ball 2 (m= kg)
θ_1				

- 4.1. What conclusions regarding the forces acting on the balls can be made by comparing the results in Table 3 to the result in Table 4?
- 4.2. Explain how the heavier ball 'feels' a larger force but have the same acceleration as the lighter ball at the same angle.
- 4.3. Express the acceleration in terms of the net force and the mass of an object.
- 4.4. Use the equations $F_{net} = ma$ and $F_{lg} = mgsin\theta$ to derive an equation that gives the acceleration along the incline in terms of the acceleration of gravity. Relate the equation to the concept of free fall.
- 4.5. Under what conditions will objects of different mass have equal accelerations on an inclined plane?
- 4.6. How does the force-mass- acceleration relationship apply to motion along i) horizontal and ii) vertical planes?
- 4.7. Two balls, A and B, of similar size are rolled upwards along identical frictionless inclined planes with the same initial velocity. The mass of A is three times the mass of B.
 - 4.7.1. How does the net force on ball A compare to the force on ball B?
 - 4.7.2. Determine the force to mass ratio for each ball.
 - 4.7.3. What does the force /mass ratio represent?

ACTIVITY 5:

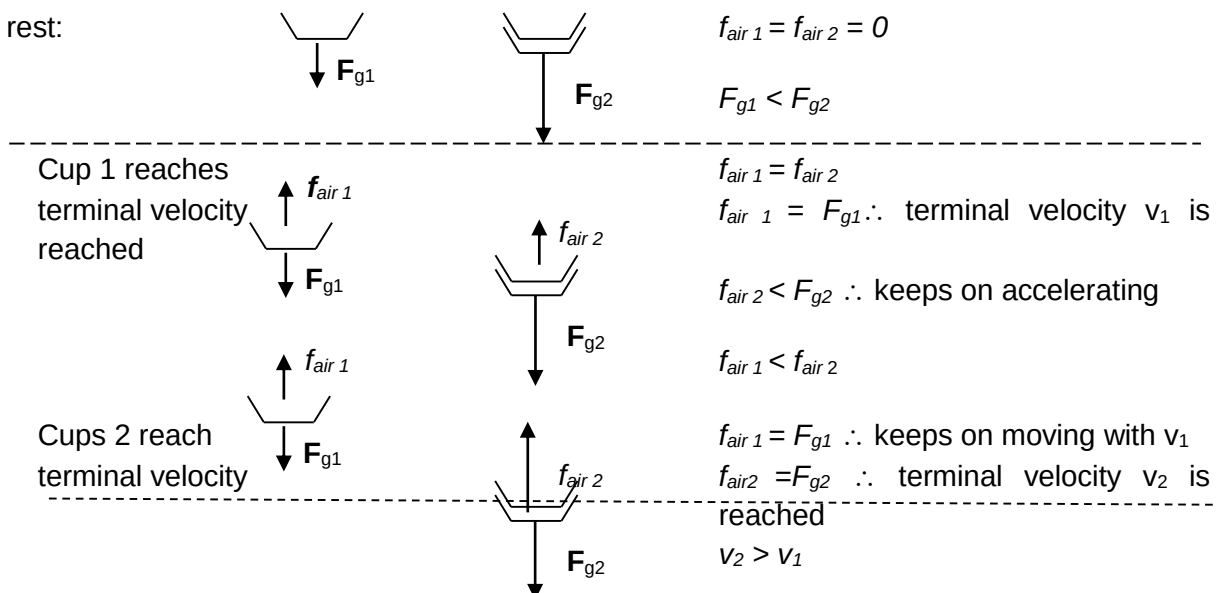
Falling cake cups

Drop one and two cake cups from the same height. Which one reaches the ground first?

The two cups placed into one another reaches the ground first.

Explanation:

At rest:



Demonstration of falling balls – explain the conditional statement ‘effect of air resistance is ignored’.

What are the consequences of ignoring air resistance?

CONCLUSION:

Write down your conclusion for the activities done. Explain the force-mass ratio in terms of your predictions and observations.

APPENDIX I: THIRD ITERATION - PRE- AND POST-QUESTIONNAIRE QUESTIONS

Physics questions:

1. Two balls of the same size have different masses. One ball is three times heavier than the other. The balls are dropped from the roof of a single story building at the same instant in time. Ignore the effect of air resistance. The time it takes the balls to reach the ground below will be:
 - A. Three times as long for the heavier ball as for the lighter one.
 - B. Longer for the heavier ball, but not three times as long as for the lighter ball.
 - C. Three times as long for the lighter ball as for the heavier one.
 - D. Longer for the lighter ball but not three times as long as for the heavier ball.
 - E. The same time for both balls.
2. How will the final velocity of the balls in question one compare?
 - A. The velocity of the heavier ball will be three times the velocity of the lighter ball.
 - B. The heavier ball will reach the larger final velocity but not three times that of the lighter ball.
 - C. Both will reach the same velocity.
 - D. The lighter ball will reach the larger final velocity but not three times that of the heavier ball.
 - E. The lighter ball will reach a velocity three times that of the heavier ball.
3. A crate containing densely packed table tennis balls and a crate containing golf balls are the same size but the golf ball crate has a larger mass. The two crates are released from rest along two identical frictionless inclined planes at the same time. Ignore the effect of air resistance and friction. Which statement regarding their respective speed at the bottom of the plane is true?
 - A. The crate with table tennis balls will have the larger speed, because lighter objects are easier to accelerate
 - B. They will reach the ground with the same speed because the force of gravity is the same for both.
 - C. They will reach the ground with the same speed because they travel the same distance.
 - D. They will reach the ground with the same speed because they have the same acceleration.

- E. The golf ball crate will have the larger speed, because its larger weight causes greater downward acceleration.
4. Martin has a cricket ball (mass $2m$) while Bob has a tennis ball (mass m). They throw the two balls vertically upwards with the same initial velocity. Ignore the effect of air resistance and friction. Which statement regarding the time for the balls to reach their respective maximum heights is true?
- A. The time will be the same because the height of the cricket ball will be lower than that of the tennis ball.
- B. The time will be the same because they reach the same height.
- C. The tennis ball will reach its maximum height first
- D. The cricket ball will reach its maximum height first.
5. A helicopter is delivering food supplies to a disaster area. As the helicopter hovers above the depositing point, two crew members unload the supplies by dropping them from the helicopter. A crate containing pillows is unloaded at the same time as a heavier crate filled with boxes of sugar. Ignore the effect of air resistance and friction. Which one of the two crates will reach the ground first?
- A. The crate with sugar because it falls faster.
- B. The crate with the pillows because it is easier to accelerate.
- C. Both will reach the ground simultaneously because they fall with the same acceleration.
- D. They will reach the ground at the same time because they have the same force.
6. While waiting for their transport after school, two small boys race marbles down a ramp for trolleys at the school entrance. In one of the races, they pitch a glass marble against a metal marble of the same size. The mass of the metal marble is more than that of the glass marble. The two marbles are placed at the top of the incline (ramp) and released from rest at the same time. Ignore the effect of air resistance and friction. The time it takes the marbles to reach the ground below will be:
- A. The same for both marbles.
- B. Less for the lighter marble.
- C. Less for the heavier marble.
- D. Impossible to say, the angle of incline must be known.
- E. Impossible to say, the ratio of the masses must be known.
7. Consider two metal balls that are the same size, but the mass of the one ball is twice as much as that of the other ball. The balls are thrown upwards from the ground and reach

the roof of a single story building at the same time. Ignore the effect of air resistance. Which statement is true about the initial velocities?

- A. The lighter ball must have double the initial velocity of the heavier ball.
- B. Both balls must be projected with the same initial velocity.
- C. The heavier ball must have double the initial velocity of the lighter one.
- D. The heavier ball must have a larger initial velocity than the lighter ball, but not twice as much.
- E. The lighter ball must have a larger initial velocity than the heavier ball, but not twice as much.

8. Consider a glass marble and a metal ball of the same size but different mass. The two balls are rolled upwards from the bottom of an inclined plane (ramp) with the same initial velocity. They reach their respective maximum heights at the same time. If the effect of air resistance and friction is ignored, the distances the balls travel before they stop on the inclines are:

- A. Impossible to say, the angles of incline must be known.
- B. Impossible to say, the ratio of the masses must be known.
- C. Less for the lighter ball.
- D. Less for the heavier ball.
- E. Both will travel the same distance.

9. Two children on the roof garden of their house are playing with a rubber ball and a bowling ball. The two balls are the same size but the mass of the bowling ball is double the mass of the rubber ball. They drop the balls from the roof of the single story building at the same instant of time. Ignore the effect of air resistance. The downward force experienced by the balls will be:

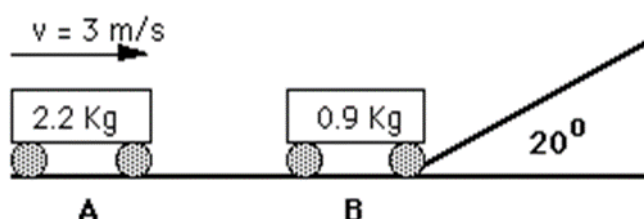
- A. Double for the rubber ball than for the bowling ball.
- B. Double for the bowling ball than for the rubber ball.
- C. Less for the rubber ball, but not half that of the bowling ball.
- D. Less for the bowling ball, but not half that of the rubber ball.
- E. The same magnitude of force for both balls.

APPENDIX J: FOURTH ITERATION - TRADITIONAL MATHEMATICAL APPROACH AND ITS LIMITATIONS

1. Traditional approach

Traditional problems – choose equation; plug in values; do the maths.

Cart A, which is moving with a constant speed of 3 m/s, has an inelastic collision with cart B, which is initially at rest as shown in the figure below. After the collision, the carts move together up an inclined plane. Neglecting friction, determine the vertical height h of the carts before they reverse direction.



- Deficiency of traditional problems:
- Unreal objects that do not tie physics to the real world.
- A picture is usually included which denies students opportunity to consider various representations.
- Physics is clearly spelled out for the students hence students don't have to decide what physics is involved.
- Assumptions are clearly spelled out denying students opportunity to figure out what is applicable.
- Variables are pre-defined for the students.
- Resulting difficulties

2. Context-Rich (Everyday problems)

You are helping your friend prepare for her next skate board exhibition. For her program, she plans to take a running start and then jump onto her heavy duty 7 kg stationary skateboard. She and the skateboard will glide in a straight line along a short, level section of track, then up a sloped concrete wall. She wants to reach a height of at least 3 m above where she started before she turns to come back down the slope. She has measured her maximum running speed to safely jump on the skateboard at 2,5 m/s. She knows you have taken physics, so she wants you to determine if she can carry out her program as planned. She tells you that she weighs 50 kg.

2.1. Advantages of real-world problems:

- Real objects tie physics to the real world.
- Choosing applicable representations helps to 'unpack' the problem

- Physics is not spelled out hence students have to decide what physics is involved.
- Assumptions are not spelled out; students have to figure out what is applicable.
- Variables are not pre-defined for the students.

2.2. Disadvantages of real world problems:

- Multiple concepts may be involved, looks difficult.
- The underlying principle/s often hidden.
- The assumptions to be made are often unclear.
- Multiple variables involved, difficult to make a prediction.
- Solutions usually require numeric calculations; exercise of mathematical skills instead of enhancing conceptual understanding.
- Lack of conceptual understanding makes it difficult to identify hidden principles.

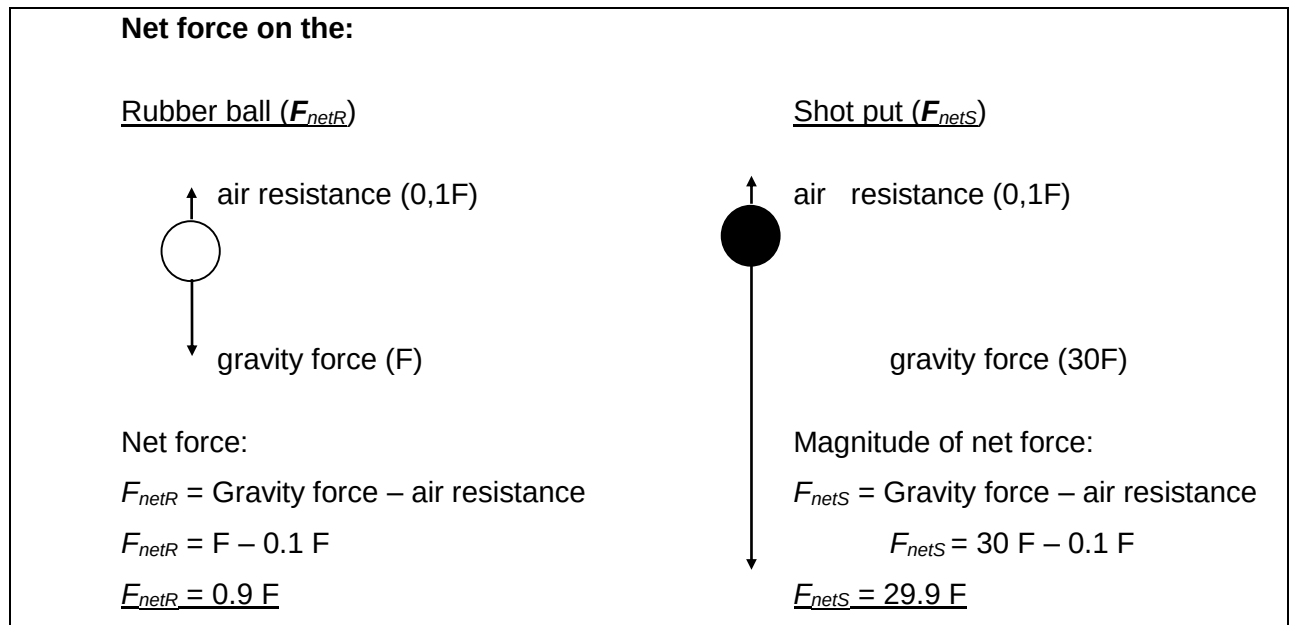
2.3. Knowledge gained from experience is different from the physics taught in class.

- All objects fall at the same rate. (Shouldn't heavy objects fall faster?)
- An object does not need a force to keep going at constant speed.
- (Everyday experience: a hockey ball needs a constant force to keep moving at a constant speed.)
- So students think some physics principles are only true in specific situations.

APPENDIX K: FOURTH ITERATION - EXPLANATION OF THE EFFECT OF AIR RESISTANCE

1. Effect of air resistance – conceptual explanation:

- a) Beginning assumption: Everything is made of particles.
- b) Every particle attracts every other particle. We have a name for this (“gravity”), BUT we cannot explain *why*.
- c) Therefore, there is a gravity force between any pair of objects, e.g. you and me, because each particle in each object attracts each other.
- d) These forces are very small. It is only when one object has a huge number of particles that the gravity force is noticeable (e.g. if one of the objects is the earth).
- e) Consider two balls of the same size but different mass e.g. a shot put and a rubber ball. There are gravity forces between the shot put and the earth, and between the rubber ball and the earth. Because the shot put has different particles and more particles (you could say the shot put has “more stuff” or, to be technically correct, more “mass”), the gravity force pulling on the shot is greater. (Empirical experimentation and calculation show about 30 times greater.)
- f) Because the shot put has “more stuff”, it needs more force pulling (or pushing) on it, for it to accelerate the same as the rubber ball (about 30 times more force).
- g) So the shot has 30 times more force pulling on it (point (5)), and needs 30 times more force on it to make it accelerate the same as the rubber ball (point (6)).
- h) The ratio : $\frac{\text{how much force is pulling or pushing}}{\text{how much stuff is being pushed or pulled}}$, determines how an object will accelerate.
- i) Therefore, IF THIS WAS ALL, the 2 balls would accelerate down together and arrive together. (And this does happen on the moon - some of you may have seen astronauts on the moon dropping a hammer and a feather; the two fell together and landed together.)
- j) But, it isn't all - on earth there is air (but not on the moon), therefore there is air resistance. Because the 2 balls are very nearly the same size and shape, the air resistance force on each is very nearly the same when they fall over short distances (2 metre or 9.6 metre).
- k) Let's say the force of gravity on the rubber ball is F. The force of gravity on the shot put will then be 30F.
- l) Suppose the air resistance force is about $1/10^{\text{th}}$ (0.1) of the gravity force on the rubber ball.



Newton's **second law** states that the acceleration of an object is dependent upon two variables - the net force acting upon the object and the mass of the object.

Newton 2: When a net force acts upon a body, it is accelerated in the direction of force. The magnitude of acceleration is directly proportional to the applied force and is inversely proportional to the mass of body.

$$a = \frac{F_{net}}{m}$$

$$ratio = \frac{\text{Net pulling force}}{\text{how much stuff is being pulled}}$$

Rubber ball

Shot put ball

$$ratio = \frac{\text{Net pulling force}}{\text{amount of stuff}}$$

$$ratio = \frac{\text{Net pulling force}}{\text{amount of stuff}}$$

$$a = \frac{F_{net}}{\text{mass}}$$

$$a = \frac{F_{net}}{\text{mass}}$$

$$a = \frac{0.9F}{1m} = 0.9g$$

$$a = \frac{29.9F}{30m} = 0.997g$$

Thus they accelerate differently and the shot put will fall faster than the rubber ball. If they fall far enough, the shot will be far enough in front that we can see the difference.

Explain the effect of air resistance with free body diagrams: Terminal velocity

F_g = force of gravity

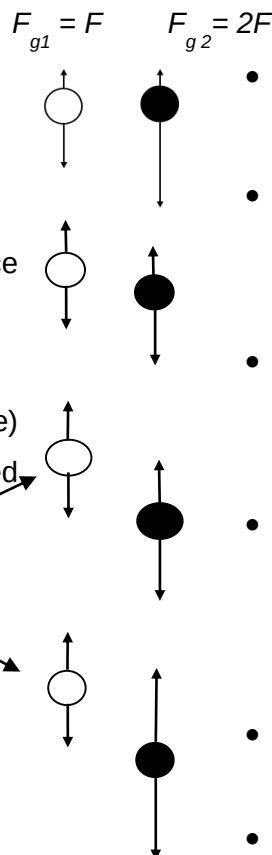
f_a = force due to air resistance

$$F_{net} = F_g - f_a$$

(For very light objects air resistance makes a difference.

If the **surface to mass ratio** is large, (like a paratrooper with a parachute) the effect of air resistance is noticed much easier.

Object 1 falls at terminal velocity



- $F_{g2} = 2 F_{g1}$ and because f_a = same on both cups, $F_{net2} > F_{net1}$
- As v increases, f_a also increases, so the net force on both objects decrease but still $F_{net2} > F_{net1}$
- Because F_{g1} is less than F_{g2} , the force due to air resistance will equal F_{g1} before it equals F_{g2}
- Hence, f_a equals F_{g1} faster than f_a equals F_{g2} ,
 $F_{net1} = 0$ so it reaches terminal velocity before object 2 does.
- $F_{net2} > 0$; object 2 is still accelerating
- Thus: when $F_{net2} = 0$; its speed is noticeably higher than that of object 1.

APPENDIX L: FOURTH ITERATION - INTRODUCTION TO QUALITATIVE PROPORTIONAL REASONING

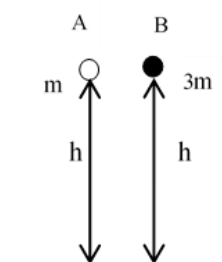
Using different representations and physics equations as reasoning tools to improve understanding of underlying principles and relationships between variables.

1. Physics equations as reasoning tools

Example 1: Two balls of the same size have different masses. One ball is three times heavier than the other. The balls are dropped from the roof of a single story building at the same instant in time. Ignore the effect of air resistance. Compare the **time** it takes the balls to reach the ground below.

Steps to guide your thinking:

- What physics is involved? Linear downwards motion
- (iii) Use a representation to 'unpack' the problem.



- (iv) 'Cleaning the problem': What assumptions are made to simplify the problem?
 - No friction or air resistance
- (v) What information regarding different physics variables is given or *implied*?
 - Same initial velocities = 0 (dropped)
 - Travel same distance (same height)
 - Acceleration = g (free fall)
 - Only force on objects is force of gravity
- (vi) What physics quantities are involved?
 - (as in iv and time)
- (vii) What relationship exists between the magnitudes of physics quantities?
 - $F_{net} = ma$
 - $\Delta y = v_0 \Delta t + \frac{1}{2} a \Delta t^2$ ($v_0=0$) (Δy = distance from starting point to end point = h)

Solve the problem:

Determine force-mass-acceleration relationship

	Ball A	Ball B
a	g	g
v₀	0	0
Δy	h	h

For Ball A (mass = m)

For Ball B (mass = 3m)

$$\Delta y = v_0 \Delta t + \frac{1}{2} a \Delta t^2 \quad (v_0=0)$$

$$\Delta y = v_0 \Delta t + \frac{1}{2} a \Delta t^2 \quad (v_0=0)$$

Δy = same for both

$v_0 \Delta t = 0$ for both

$\frac{1}{2} a =$ same for both

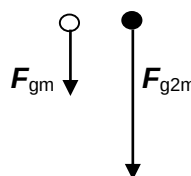
$\Rightarrow \Delta t^2$ will be same for both

They will reach the ground at the same time.

Example 2: Two children on the roof garden of their house are playing with a rubber ball and a bowling ball. The two balls are the same size but the mass of the bowling ball is double the mass of the rubber ball. They drop the balls from the roof of the single story building at the same instant of time. Ignore the effect of air resistance. How does the downward force experienced by the respective balls compare?

Steps to guide your thinking:

- What physics is involved?
Net force
- Use a representation to 'unpack' the problem
Free body diagrams
- 'Cleaning the problem': What assumptions are made to simplify the problem?
No friction or air resistance, hence force of gravity = net force
- What information regarding different physics variables is given or *implied*?
Different mass
Gravitational force only force acting on balls.
- What physics quantities are involved?
Force of gravity and mass
- What relationship exists between the physics quantities?
 $F = mg$



Solve the problem:

$$F = mg \text{ (g = gravitational acceleration)}$$

Rubber ball (mass = m)

$$F_{\text{rubber}} = mg$$

Bowling ball (mass = 2m)

$$F_{\text{bowling}} = 2mg$$

Force of gravity on bowling ball is twice that of the rubber ball.

Conceptual question:

How come the magnitudes of the force of gravity differ but objects have the same acceleration?

Example 3: Use the relationship between the physics variables to consider each one of the options given to help you choose the most correct option.

A heavily loaded truck and a motorcar travel side by side on a highway. The two drivers notice the green traffic light changing to orange and step on the brakes on their respective vehicles at the same instant of time and come to a halt just as the traffic light turns red. Ignore the effect of air resistance and friction. In order for them to have come to a standstill at the crossing at the same time,

- The force applied by the brakes in both vehicles must have been the same.
- The heavy truck must have started braking long before the car.
- The acceleration caused by the respective braking forces must have been the same.

Steps to guide your thinking:

What physics is involved? Linear motion

- Use a representation to 'unpack' the problem.



- Cleaning the problem': What assumptions are made to simplify the problem?

No friction or air resistance.

- What information regarding different physics variables is given or *implied*?

Same initial velocities (side by side)

Travel same distance

Final velocity = 0 (come to halt)

Mass of truck larger than mass of car

- What physics quantities are involved?

Same as in iv, acceleration (negative) and force due to braking.

- What relationship exists between the physics quantities?

$$v_1^2 = v_0^2 + 2a\Delta x \quad (\Delta x = \text{distance between starting point and end point})$$

Solve the problem:

$$v_1^2 = v_0^2 + 2a\Delta x \rightarrow a = \frac{v_1^2 - v_0^2}{2\Delta x}$$

$$\therefore \text{ If } v_1^2_{truck} = v_1^2_{motor car}; \quad v_0^2_{truck} = v_0^2_{motor car} \text{ and } \Delta x_{truck} = \Delta x_{car};$$

then $a_{truck} = a_{car}$

$$F_{net} = ma: \quad F_{truck} = m_{truck}a \quad \text{and} \quad F_{car} = m_{car}a \quad \text{but } m_{truck} > m_{car}$$

$$\text{Therefore} \quad F_{truck} > F_{car}$$

2. Blending multiple representations

Example 4a). A car (mass M) and a truck (mass $2M$), move from rest with equal accelerations over different distances at the same time. The distance over which the truck is accelerated is twice that of the car. Ignore the effect of air resistance and friction.

- Which vehicle will have the larger velocity at the finishing line?
- Which vehicle will reach the finishing line first?

Solution 4a



	Truck	Car
v_1	$v_1 = ?$	$v_1 = ?$
v_0	$v_0 = 0$	$v_0 = 0$
Δx	$2d$	d
a	a	a

Relationship between physics variables: $v_1^2 = v_0^2 + 2a\Delta x$

For truck:

$$v_t^2 = 0^2 + 2a(2d)$$

$$v_t^2 = 2(2ad)$$

$$v_t^2 = 2(v_c^2)$$

For car:

$$v_c^2 = 0^2 + 2a(d)$$

$$v_c^2 = 2ad$$

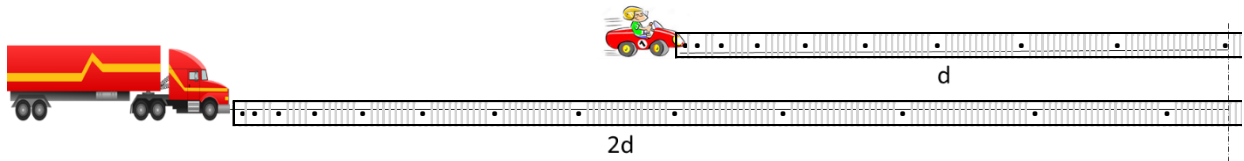
$$\therefore v_t = \sqrt{2} v_c \Rightarrow \underline{\text{The truck will have the larger speed.}}$$

Conceptual question: If objects with different masses have the same acceleration, how do the net forces compare?

Example 4b) Which of the vehicles will reach the finishing line first?

Solution 1: Solve by means of motion diagram

Motion diagram indicate same acceleration.



Solution 2: By means of equation: $v_1 = v_0 + a\Delta t$

$$\therefore \Delta t = \frac{v_1 - v_0}{a} \quad v_1 \text{ for truck is } > v_1 \text{ for the car therefore if } a_{\text{truck}} = a_{\text{car}}$$

then $\Delta t_{\text{truck}} > \Delta t_{\text{car}}$

Solution 3: By means of equation: $\Delta x = v_0 \Delta t + \frac{1}{2} a \Delta t^2$ ($v_0=0$)

For truck

for car

$$2d = 0 + \frac{1}{2} a \Delta t_t^2$$

$$d = 0 + \frac{1}{2} a \Delta t_{\text{car}}^2$$

$$\frac{1}{2} a \Delta t_t^2 = 2d$$

$$\frac{1}{2} a \Delta t_{\text{car}}^2 = d$$

$$\Delta t_t^2 = \frac{2d}{a}$$

$$\Delta t_{\text{car}}^2 = \frac{d}{a}$$

$$\therefore \Delta t_{\text{truck}} > \Delta t_{\text{car}}$$

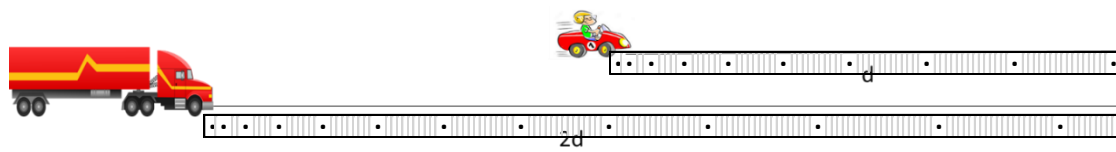
$\Rightarrow$ the car will reach the finish line first.

APPENDIX M: FOURTH ITERATION - TUTORIAL PROBLEMS

CONCEPTUAL REASONING

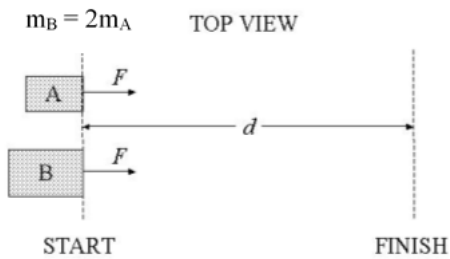
1. Consider two metal balls that are the same size, but the mass of the one ball is twice as much as that of the other ball. The balls are thrown upwards from the ground and reach the roof of a single story building at the same time. Ignore the effect of air resistance.
 - 1.1. How do the net forces on the balls compare?
 - 1.2. Use the mathematical expression of Newton's second law to compare the accelerations of the balls.
 - 1.3. How do their **initial velocities** compare?
2. Two cars, A (mass M) and B (mass $2M$), are moved from rest at the same acceleration over different distances and at different times. The distance over which B is accelerated is twice that of car A. Car B is moved first. Car A is moved at the exact moment that car B passes car A at distance d . Ignore the effect of friction.

Use the motion diagrams to determine which car will reach the finishing line first. Explain your reasoning.



3. Bob and Martin climb up a tree. Bob, whose mass is double that of Martin, reaches twice the height as Martin does above the ground when he loses his footing and falls. Martin is so concerned for his friend that at the exact moment Bob passes him on his way down; he loosens his grip and falls down as well. Ignore the effect of air resistance.
 - 3.1. How do the accelerations of the boys compare?
 - 3.2. Which boy will experience the greater net force?
 - 3.3. Who will reach the ground first?
4. Consider a glass marble and a metal ball of the same size but different mass. The mass of the metal ball is twice the mass of the marble. The two balls are rolled upwards from the bottom of an inclined plane (ramp) with the same initial velocity. Ignore the effect of air resistance and friction.
 - 4.1. Use physics equations in symbolic form to compare the net forces on the balls.
 - 4.2. Use a physics equation in symbolic form to show why the balls have the same negative accelerations although net forces on the balls differ in magnitude.
 - 4.3. Compare the maximum **heights** the balls reach up the incline.

5. Two blocks are initially at rest on a frictionless horizontal surface. The mass of block B is twice the mass of block A. The same constant force F is applied and the blocks are pulled through the same distance along a straight line as shown in the diagram. The constant force is applied for the entire distance. Ignore the effect of air resistance and friction.



- 5.1. Use applicable equations to show your reasoning.
- 5.2. How do the accelerations of the blocks compare?
- 5.3. How much will the final velocity of B be compared to A?
- 5.4. Which block will reach the finishing line first?

APPENDIX N: ETHICAL CLEARANCE CERTIFICATE



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Ethics Committee

Tel +27 18 299 4852
Email Ethics@nwu.ac.za

ETHICS APPROVAL OF PROJECT

The North-West University Ethics Committee (NWU-EC) hereby approves your project as indicated below. This implies that the NWU-EC grants its permission that provided the special conditions specified below are met and pending any other authorisation that may be necessary, the project may be initiated, using the ethics number below.

Project title: Investigating conceptual knowledge of first year physics students in solving multivariate mechanics problems.

Project Leader: Dr M Lemmer

Ethics number:

N	W	U	-	0	0	0	5	3	-	1	4	-	A	3
Institution				Project Number							Year		Status	

Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Approval date: 2014-06-06

Expiry date: 2019-06-05

Special conditions of the approval (if any): None

General conditions:

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, please note the following:

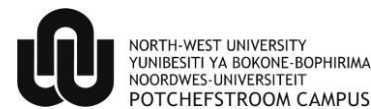
- The project leader (principle investigator) must report in the prescribed format to the NWU-EC:
 - annually (or as otherwise requested) on the progress of the project,
 - without any delay in case of any adverse event (or any matter that interrupts sound ethical principles) during the course of the project.
- The approval applies strictly to the protocol as stipulated in the application form. Would any changes to the protocol be deemed necessary during the course of the project, the project leader must apply for approval of these changes at the NWU-EC. Would there be deviation from the project protocol without the necessary approval of such changes, the ethics approval is immediately and automatically forfeited.
- The date of approval indicates the first date that the project may be started. Would the project have to continue after the expiry date, a new application must be made to the NWU-EC and new approval received before or on the expiry date.
- In the interest of ethical responsibility the NWU-EC retains the right to:
 - request access to any information or data at any time during the course or after completion of the project;
 - withdraw or postpone approval if:
 - any unethical principles or practices of the project are revealed or suspected,
 - it becomes apparent that any relevant information was withheld from the NWU-EC or that information has been false or misrepresented,
 - the required annual report and reporting of adverse events was not done timely and accurately,
 - new institutional rules, national legislation or international conventions deem it necessary.

The Ethics Committee would like to remain at your service as scientist and researcher, and wishes you well with your project. Please do not hesitate to contact the Ethics Committee for any further enquiries or requests for assistance.

Yours sincerely

Prof Amanda Lourens
(chair NWU Ethics Committee)

APPENDIX O: CONSENT FORM



NORTH-WEST UNIVERSITY

CONSENT TO PARTICIPATE IN RESEARCH

Researchers:

Dr M. Lemmer and Mrs A. Ferreira

Study title:

Investigating students' solving of kinematics problems in various contexts.

You are requested to participate in a research study conducted by Annalize Ferreira from the School of Science, Mathematics and Technology Education, Faculty of Natural Sciences, North-West University (Potchefstroom Campus). The research results of this study will be reported in the form of scientific publications. You were selected as a participant in this study because you are a B.Ed. Honours student in Science Education.

PURPOSE OF THE STUDY

The purpose of this study is to investigate the knowledge that students use in solving kinematics problems in various contexts.

The main research question that will guide this study reads: *To what extent do students apply physics concepts in corresponding kinematic problems in various contexts?*

PROCEDURES

If you agree to participate in this study, we will ask you to complete the questionnaire.

POTENTIAL RISKS AND DISCOMFORTS

The study to be undertaken will not provide any potential risks to the participant. The results of this study will not be included in the assessment of the student's Physics marks.

POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

This study is conducted specifically for the Faculty of Natural Sciences, North-West University (Potchefstroom Campus). Your participation may lead to reevaluation and adjustments of current teaching strategies in Physical Sciences.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Information identifying any individual will not be released to any other party for any reason. Completion of the questionnaire is not anonymous because pre- and post-instruction results will be compared. The final results of this study will be made available to participants on request.

PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and still remain in the study. The researcher may withdraw you from this research if circumstances arise which warrant doing so.

IDENTIFICATION OF RESEARCHERS

If you have any questions or concerns about the research, please feel free to contact Dr Miriam Lemmer (study leader) at 0182994270 or Mrs Annalize Ferreira (researcher) at 0834627500

RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, please ask the researchers or promoter of the study.

SIGNATURES OF PARTICIPANT

The information above was described to me by Annalize Ferreira (researcher) in English and I am in command of this language.

I hereby consent voluntarily to participate in this study. I understand that this form will be stored by the researcher in case of any queries.

_____ *Name of Participant*

_____ *Signature of Participant*

..... *Date*

Complete the questionnaire by marking the appropriate number on the questionnaire. Thank you for participating in this survey.

Constants and Equations you may need:

Konstantes en Vergelykings		Constants and Equations
Vir gravitasieversnelling moet hierdie waarde altyd gebruik word, tensy anders in vraag gemeld.	9,8 m/s ²	This value of acceleration due to gravity must always be used, unless stated otherwise in question.
Bewegingsvergelykings met konstante versnelling (vir x en y)	$v = v_0 + at$ $x = x_0 + v_0t + \frac{1}{2}at^2$ $v^2 = v_0^2 + 2a(x-x_0)$	Equations of motion with constant acceleration (for x and y)

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

