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**A Phenomenographic Study of Introductory Physics Students:
Approaches to Problem Solving and Conceptualisation of Knowledge**

By

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A thesis submitted to the Dublin Institute of Technology,
for the degree of Doctor of Philosophy (PhD)

Supervisors: Dr. Brian Bowe and Dr. Robert Howard

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DECLARATION

I certify that this thesis which I now submit for examination for the award of doctor of philosophy, is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for an award in any other Institute or University.

The work reported on in this thesis conforms with the principles and requirements of the Institute's guidelines for ethics in research.

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ABSTRACT

This phenomenographic study presents a description of the approaches to problem solving and conceptualisation of physics knowledge of introductory physics students, specifically in the context of the Irish higher education system. Much research has been carried out that has shown that physics students are not developing the conceptual knowledge necessary to become adept problem-solvers. This may be due to the traditional physics education assumption that students will develop an understanding of the conceptual nature of physics by repetitively solving quantitative problems. However, research has shown that this is not the case and that education and the curriculum needs to explicitly reflect the qualitative and quantitative nature of physics.

This empirical study was conducted using phenomenographic assumptions and methodology to collect, analyse and interpret data from forty two individual semi-structured interviews with introductory physics students. This study presents a systematic way of identifying the variations in the students' approaches to problem solving, the variations in these students' conceptual awareness, and an assessment of the effect this has on student learning.

The findings from this study reveal that novice physics students' approaches to problem solving can be described by five qualitatively and critically different categories. Also these students' conceptual awareness in the context of mechanics can be described by four qualitatively and critically different categories. The findings suggest that in order for these

students to develop as problem solvers they must have developed an awareness of the conceptual nature of physics.

This research provides an insight into and a better understanding of the way introductory physics students approach problem solving and of the development of their conceptual knowledge. It will inform teaching and assessment practices, not only in physics education but also in other disciplines so that higher level education can produce better problem-solvers for industry, research and a knowledge-based society.

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For Jeanette Therese

With love and gratitude.

Mammy this is and always was for you.

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CHAPTER 1

INTRODUCTION AND CONTEXT

1.1 Introduction

This research study set out to examine physics students' conceptualisation of knowledge and approaches to problem solving in the context of the Irish higher education system. It is a prerequisite of any physics course that the graduate be an adept problem-solver with the ability to conceptualise and transfer their understanding and knowledge in order to approach novel problem situations. Many students entering higher level education have difficulties in achieving these objectives and this is particularly true when the students have no prior formal physics education, as in the Irish higher education system. The idea that higher level students have difficulties effectively learning physics is not a new one and numerous studies carried out throughout the world over the past fifty years have highlighted these difficulties (many of these studies are discussed in Chapter 2). This is not surprising; physics is a complex and often counterintuitive subject to study, especially when it is only formally introduced to an individual at 16 – 19 years of age.

Previous research has shown that students will not develop an understanding of the conceptual nature of physics by solving quantitative problems (Kim & Pak, 2002) even though, historically, physics education tends to rely on this assumption. Some research has found that students cannot develop as problem-solvers without first having the 'required'

conceptual understanding (Hake, 1998; Knight, 2002). However, the connection between conceptual knowledge and problem solving has not been as well studied as these individual areas in physics education research (Hoellwarth *et al.*, 2005; Heron & Meltzer, 2005). This study set out to discover the qualitatively different ways in which introductory physics students approach problem solving and the variations in their conceptual awareness within the context of the Irish higher education system. This will in turn inform curriculum design and teaching and assessment practices in order to improve students' learning and problem solving abilities leading to better problem-solvers who have developed the capability to approach 'real world' and complex problems in more powerful ways. Real world and complex problems refer to problems which take place in an everyday context and are not of a highly structured algorithmic nature. It was a recommendation of the Physical Science Task Force to the Irish Government (Report of the Task Force on the Physical Sciences, 2002) to increase recruitment to science, engineering and technology courses by improving the teaching and learning experience within science departments. The processes used to achieve the aims of the research will be an outcome of the work and will be transferable to other disciplines, particularly in science and engineering.

1.2 Context of research

In recent years there have been two distinct drivers which have led to transformations in science education; changes in student profile and education research. The changes in student profile stem from mass education, dramatic changes in information technology and the decline of student numbers in science education. The term 'mass education' refers to an education system that is open to students from diverse backgrounds, abilities and ages. The problems this causes have been described by Wagner (1995, pg 361):

The problems faced by mass higher education arise from a system, which has become mass in its size but remains elite in its values. The recent external changes of numbers, structures, finance and governance have not been matched by appropriate internal changes of values, purpose and activity.

The changes in information technology, in particular the rise of the Internet, have also led to changes in student learning and studies. This technology has opened the doors for new teaching methodologies which have been progressively named computer-assisted learning, e-learning and online learning. Added to these changes, physical science education has faced a crisis over the past few years as annually fewer students choose to pursue science at all levels of education (Institute of Physics, 2001; Knight, 2002). In the context of Irish higher education, the drop in student applicants has meant that new entrants to physics courses have less prior physics knowledge and are not as motivated as students in previous

years which has put pressure on physics educators to recruit students and improve retention rates.

These factors have led science educators in higher education to not only take a critical look at what is being taught but also how this is being taught (Institute of Physics, 2001). Therefore in the last thirty years the importance and need for science education research has led to the development of many research groups, many of whom have undertaken projects to get a better understanding of how students learn and how educators can help students learn and develop an understanding of the subject. Education research, where the emphasis is on theory and practice, has already shown the importance of student-centred (O'Neill & McMahon, 2005) and lifelong learning (OECD, 1998; Fischer, 2000). This has led to a paradigm shift in higher education. Curriculum design has now moved from the teacher-centred syllabus curriculum design to student-centred learning outcome curriculum design where a learning outcome is defined as a statement of what the learner is expected to be able to do on successful completion of the module to demonstrate their knowledge, understanding, skills and/or competences.

Science education research, where the emphasis is on how students learn and develop understanding, had largely been ignored among science educators for many years. Since 1999 the School of Physics in the Dublin Institute of Technology has been critically analysing its pedagogical strategy, leading to a reconsideration of teaching and assessment practices. In July 1999, the School started investigating the feasibility of using more student centred approaches in physics education and through consultation with other educators and

members of the DIT's newly formed Learning and Teaching Centre possible approaches to physics education were devised. In 2001 the School of Physics set up the Physics Education Research Group to carry out research to inform curriculum development, teaching and assessment practices. In the same year members of the group engaged in collaborative action research in order to design, implement and evaluate a first year physics problem based learning course (Bowe, 2007). Problem based learning is now the primary pedagogical method of delivery of introductory physics within the School of Physics. This will be discussed in further detail in section 1.4 below.

As mentioned previously, physics graduates are required to be adept problem-solvers with the ability to conceptualise and transfer their understanding and knowledge, but research has shown that students may not be developing the conceptual understanding necessary for this to be achieved (Van Heuvelen, 1991a). Research in physics education has also reiterated research from cognitive psychology indicating that for students to develop an understanding of the conceptual nature of physics, education must first start with their prior conceptions (Roth, 1990). These prior conceptions are said to be remarkably resistant to change as conventional instruction makes almost no difference to a student's conceptual beliefs (Halloun & Hestenes, 1985a). The teaching approach must allow for students to restructure their own understanding by first seeing where, when and why their conceptions fail and only after this can students start to build up a new and correct understanding. The Physics Education Research Group in DIT initially based their pedagogical approaches on this, the constructivist view of learning and teaching.

However, more recently in physics education research there has been a shift from examining what and how physics is being taught to examining how the student is experiencing the learning situation (Ingerman *et al.*, 2007; Linder *et al.*, 2006; Scherr & Redish, 2005) in an effort to connect “the huge amount of research work done on learning outcomes and conceptual difficulties to the dynamics of learning and teaching practice, and thus informing the crafting of teaching practice” (Ingerman *et al.*, 2008, pg 2). Much of this research focuses on learning ‘as it happens’ and employs the phenomenographic notion of experiencing *variation* as the basic mechanism of learning (Marton & Booth, 1997; Marton & Tsui, 2004; Marton & Pang, 2006). The premise of this notion is that for learning to occur an individual must experience variation within the object to be learned and that variation must be discerned within the critical features of the object to be learned. This is explained in more detail in Chapter 3 when the rationale for the assumptions upon which this research is based is described.

This research provides an insight and a better understanding into introductory students’ approaches to problem solving, their conceptualisation of knowledge and the relationship between them. It does this by providing a description of the qualitatively different ways in which these students approach problem solving and of the variations in their conceptual awareness. Awareness is defined as the totality of a person’s experiences of the world at each point in time (Marton & Tsui, 2004). Conceptual awareness within the context of this study is therefore defined as the totality of the students’ experiences of the concepts encountered. The process of conceptualisation of physics knowledge refers to the ways in which students experience, perceive, conceive and understand physics concepts and

knowledge. The study provides a description of a set of students' experience of physics, in particular mechanics, in the phenomenographic sense. The term *experience* here does not specifically refer to knowledge of or involvement in physics but instead refers to how the students are aware of the physics that they encounter.

The findings from this study should encourage the development of students' problem solving skills by highlighting for students and educators the critical variations and limitations of approaches that are used. The findings will give lecturers an insight into the variations in their students' knowledge and approaches and be used to encourage the development of more complete awareness and effective problem-solving approaches through the use of appropriate learning activities. The findings will also encourage the development of constructive alignment (Biggs, 1999) within the design of curricula, so that learning activities and assessment will be aligned with the learning outcomes of the curricula.

1.3 Research setting

1.3.1 Third level entry system

The National Qualifications Authority of Ireland (NQAI, 2009), established in 2001, determines the policies and criteria for the National Framework of Qualifications (NFQ) in Ireland. The NQAI itself has three primary objects that relate to the framework:

- The establishment and maintenance of a framework of qualifications for the development, recognition and award of qualifications based on standards of knowledge, skill or competence to be acquired by learners;
- The establishment and promotion of the maintenance and improvement of the standards of awards of the further and higher education and training sector, other than in the existing universities; and
- The promotion and facilitation of access.

The NQAI determined that the framework would be based on levels, where each level has a specified level indicator. The framework consists of 10 levels and the levels set out a range of standards of knowledge, skill and competence. In short the levels relating to higher education awards in Ireland are as follows:

Level 10: Doctoral Degree

Level 9: Masters Degree and Post-graduate Diploma

Level 8: Honours Bachelor Degree and Higher Diploma

Level 7: Ordinary Bachelor Degree

Level 6: Advanced Certificate and Higher Certificate

Level 5: Level 5 Certificate

Level 4/5: Leaving Certificate

Almost all students who participated in this study enrolled in the Dublin Institute of Technology following completion of the Irish Leaving Certificate. The Irish third level entry system is based on a CAO (Central Applications Office) points system whereby a certain number of points are allocated to each grade achieved in the Leaving Certificate examinations. The maximum number of points is 600 and this is based on a Leaving Certificate result of six A1s at honours level. In secondary school students can choose to study each subject either at ordinary (lower) level or honours (higher) level; students usually study seven subjects but only the results from the best six are taken into account. An A1, representing a grade of 90% or better, in an honours subject merits 100 CAO points, whereas an A1 in an ordinary level subject merits 60 points. A complete table of CAO points and the corresponding grades can be seen in Appendix A. The students participating in this research had CAO points ranging from 160 to 530; however, the study also included students who transferred from other courses and those who entered their programme of study on an interview basis (e.g. mature students – students over 25 who have returned to education after a period of two or more years). Therefore the students who participated in this study entered third level education with a range of abilities and almost 70% of them had not studied physics for the Leaving Certificate.

The students who participated in this study were enrolled in a wide variety of scientific programmes. Three of these programmes were 4-year honours degrees in a physics discipline (level 8), these were:

- Physics Technology
- Physics with Medical Physics and Bioengineering
- Science with Nanotechnology

One was a 3-year ordinary degree (level 7) in science, Physical and Life Sciences. The introductory physics in year 1 in all of these programmes is now delivered through problem based learning, which is discussed in some detail below. The remainder of the programmes are those in which a subject other than physics is the major and the introductory physics in these programmes is delivered through traditional methods. To clarify at this point, a “programme” refers to an entire degree programme which is offered by the Institute whereas a “course” refers to an element within the programme (for example the introductory physics course in the first year of study). “Modules” are units of learning and each module is assigned a set number of ECTS credits. For example within the 4 year Physics Technology programme, the first year physics course consists of 2 modules, each 10 ECTS credits.

1.3.2 Problem based learning (pbl)

Problem based learning is a pedagogical approach designed to help students develop self-directed learning skills and the aim is to promote deep learning in order to achieve higher levels of cognitive learning and to develop a thorough understanding of the subject (Bowe

& Cowan, 2004). Instead of the traditional, situation-specific problems or exercises which have well defined parameters and a predefined outcome synonymous with introductory physics courses, students are faced with context rich, 'real world', open-ended problems in a group setting.

Problem based learning emerged in the 1960s to enable medical students to apply and synthesise knowledge through using 'real life' case studies (Barrows & Tamblyn 1980; Boud & Feletti, 1997). It has since gained in popularity across diverse subjects such as law, business studies, engineering and medical/healthcare (for example see: Alavi, 1995; Pereira, 1998; Allen *et al.*, 2001; Clouston & Whitcombe, 2005). Problem based learning has been implemented in physics in the last ten years (for example see: Duch *et al.*, 2001; Van Kampen *et al.*, 2004; Raine & Symons, 2005) and was introduced in the DIT physics courses in 1999 (Bowe & Cowan, 2004) although elements of it have been used throughout the physics community under the name of co-operative learning for a longer period of time (for example see Heller & Hollabaugh, 1992). Under the principles of problem based learning there are four main learning categories with subsets of skills that a post problem based learning student should have acquired (Schmidt, 1993): Affective, Intellectual, Social and Study skills. Affective refers to the ability to demonstrate confidence and apply critical thinking to manage unfamiliar situations. Intellectual relates to the ability to work with different levels of uncertainty and the ability to appraise different sources of information. Social skills refer to the ability to collaborate in groups, learn from others, and facilitate others' learning and communication of understanding through a variety of media. Study refers to the development of life-long learning skills which includes the abilities to recognise the limits of an individual's own competence and learn from mistakes, practice

self-directed learning, ask relevant questions, clarify what knowledge and experiences are needed to understand a new situation, reflect and appraise performance of self and others. According to Dolmans *et al.* (2005, pg 732), “problem-based learning has the potential to prepare students more effectively for future learning because it is based on four modern insights into learning: constructive, self-directed, collaborative and contextual”. These four insights are shaped into the above learning categories. Problem based learning is also designed to integrate the subject knowledge students require to solve a particular problem and therefore study issues at a deep rather than surface level (Entwistle & Ramsden, 1983). ‘Real life’ problems are used as the initial triggers for learning and to create a point at which new learning or critical thinking can be applied and reapplied until understanding is achieved.

According to Dolmans *et al.* (2005), there are three essential characteristics of problem based learning: problems as a stimulus for learning, tutors as facilitators and group work as stimulus for interaction. Different approaches can be put forward to tackle learning issues or the use of student roles to stimulate interaction but these are often subject specific and the implementation of problem based learning comes down to the use of the above mentioned essential features. Typically, problems are written “to guide students towards certain subject matter” (Schmidt & Moust, 2000, pg 20) and the problem should describe phenomena or events that students may observe in every day life (Schmidt, 1983). Norman & Schmidt (2000) conclude in their review that there is a strong theoretical basis for the idea that students learning through problem based learning may be better able to transfer concepts to new problems, and that there is some preliminary evidence to this effect.

In engineering and physics the use of problem solving learning is well established (see many of the introductory physics textbooks, such as Young *et al.*, 1999; Wilson & Buffa, 2002) but it is important to have a clear understanding of the distinction between learning via problem solving and learning via problem based learning. In learning via problem solving the students are first presented with the material, usually in the form of a lecture, and are then given problems to solve. These problems tend to be narrow in focus, test a restricted set of learning outcomes, and usually do not assess any key skills. The students may not necessarily get the opportunity to evaluate their knowledge or understanding, to explore different approaches, nor to link their learning with their own need as learners. They usually have limited control over the pace and style of learning and hence this method tends to promote surface learning (Bowe & Cowan, 2004). In problem based learning, the students determine their learning issues and develop their unique approach to solving the problem.

Due to its social aspect and the use of 'real' problems, problem based learning also shares many similarities with enquiry based learning (Grandis *et al.*, 2003), context based learning (Hansman, 2001) and project based learning (Blumenfeld *et al.*, 1991; Mills & Treagust, 2003). Indeed the boundaries between these pedagogical approaches are often blurred and ambiguous.

1.3.3 Level 8 problem based learning course

The problem based learning course which is delivered to students entering their first year of the level 8 physics degree programmes was set up in 2001 (Bowe & Cowan, 2004; Bowe, 2005, 2007). The students, who work in groups of four or five, have four hours of pbl classes per week. During this time they must brainstorm to identify ‘ideas’, ‘facts’, ‘learning issues’ and ‘tasks’, for a problem based on a subject for which they have received no formal instruction. The students may use any resources that are available to them and are encouraged to complete the problem by the end of the second two-hour session. The students are expected to work as a group both during and outside class time in order to solve the problem. They must then present the problem in a predefined manner before the next problem is undertaken. The role of the ever-present tutor in the class is to facilitate learning by asking probing questions, where necessary, guiding the students and continually assessing the students’ progress. In conjunction with the classes is a three-hour project based laboratory and a one-hour tutorial. The tutorial takes the form of a recitation period during which students are given the opportunity to solve typical end of chapter algorithmic problems in the presence of a tutor or supervisor. An example of the first problem based learning problem given to these students during the mechanics section of the module is provided in Appendix B1. The students are assessed formatively and summatively throughout the year and end of semester exams are open book exams.

1.3.4 Level 7 problem based learning course

Problem based learning was introduced as a method of delivery to the level 7 science course in 2006 in an effort to increase retention rates and to promote interest in continuing with physics in the second year of study. The classes are run in much the same way as the level 8 programmes; however, these students have only three hours of pbl class time as this is the class time allotted to each of the three science subjects that they study. An example of one of the first problems that these students receive is illustrated in Appendix B2. In addition the students receive a one-hour tutorial before they receive a problem on that subject; the tutorial is carried out using a form of Peer Instruction (Mazur, 1997). The tutorial in this context involves the lecturer asking a concept based question which is responded to by the students using 'clickers' (classroom response systems). The lecturer then gives a short (10 minute) lecture on the concept and asks the question again. During this the students are encouraged to discuss the question within small groups before responding and to defend their response to each other after responding. Incorporated with this is a two-hour laboratory session each week carried out in the traditional manner. These students are also assessed formatively and summatively throughout the year, but the end of semester exam is closed book.

1.3.5 Traditional lecture based course

Each of the traditional lecture-based courses involved with this study were delivered in the same manner. Each course consists of three hours of lectures per week, which are delivered

by a single lecturer. The lecturer typically delivers the course material in one of two ways: he/she may provide the students with photocopied notes containing the material and proceed by discussing and explaining the material during the lecture or he/she may use the whiteboard to deliver the material, in which case the students are expected to take their own notes. In both cases the lecturer will usually also present worked examples of problems throughout the lecture, during which time students may also be asked to solve sample problems and these problems are typically end of chapter type problems. However, the students are not required to do 'homework', although individual lecturers may suggest reading material and/or problems to attempt between classes. There is no incentive for the students to do so (e.g. continuous assessment mark). It is during the one-hour tutorial each week that students have the opportunity to reflect on the material delivered in class by solving algorithmic problems based on the material. Also incorporated into the course is a two-hour laboratory session each week, which is also carried out in a traditional manner, that is, students are presented with a lab manual and are required to carry out the experiment as per the manual guidelines. The students' learning is assessed using closed book exams at the end of the modules.

1.4 Aim and objectives of the research

As mentioned in section 1.1, the overall aim of this research was to discover the qualitatively different ways in which introductory physics students approach problem solving and to discover the variations in their conceptual awareness within the context of the Irish higher education system. The objective of the study was to achieve an overall description of the knowledge state, problem solving and conceptual, of a sample group of Irish introductory physics students prior to and following formal instruction in a specific area of physics. To set the context of the study, the research began by employing a research-based diagnostic tool in order to answer the following research questions:

- What conceptual mechanics knowledge do students have when beginning Irish Higher Education?
- Do students develop sound conceptual knowledge after formal instruction in mechanics, as measured by a diagnostic tool?

The answers to these questions will inform the reader's interpretation of subsequent findings by setting the context in terms of the level and range of understanding among the participating students (particularly in comparison to previous international studies). They also informed the selection of participants for the subsequent research.

After answering these questions, the research focused on qualitative evaluations of the students' experience of mechanics. In order to achieve the overall research objective a phenomenographic approach was used to answer the following research questions:

- What are the qualitatively different ways in which introductory physics students approach problem solving?
- What are the variations in these introductory students' conceptualisations of knowledge?

During the course of the research an interesting corollary was to investigate the relationship between the students' conceptual awareness and their approaches to problem solving. As mentioned previously the connection between conceptual knowledge and problem solving has not been well studied in the past, therefore another research question which this study set out to answer was:

- For these students what is the relationship, if any, between conceptual awareness and approach to problem solving?

Finally in order to gain a more complete description of the conceptualisation of a specific concept among the participating students in the study, a further research question was posed:

- What are the qualitatively different ways in which introductory physics students conceive the concept acceleration?

The implications that the answers to these research questions may have for physics education, physics educators and students are discussed in the final chapter (Chapter 8).

1.5 Outline of Thesis

This chapter has provided the context in which this research is based and includes a description of the research setting, followed by the aims and research questions of the study. Chapter 2 begins by providing the reader with a brief history of the evolution of physics education research followed by a discussion of various perspectives concerning the nature of student knowledge. The chapter then provides a succinct summary of the relevant literature which informed the research presented here. This literature is reflected upon later in the thesis in light of the research findings.

Chapter 3 outlines the research design, which firmly places the research within the phenomenographic tradition and describes the theoretical and methodological assumptions associated with this research tradition. It also provides the reader with a description of the methods employed to obtain and analyse the data and finally introduces the research participants.

Chapter 4 is the first of the findings chapters and contains, as its point of departure, quantitative data pertaining to the conceptual knowledge state of the participating students. The quantitative data are first presented as pre-instruction and post-instruction findings and are then discussed in relation to previous relevant research in the area. Chapters 5 to 7 are the phenomenographic findings chapters in which the outcome spaces (which will be discussed in more detail in Chapter 3) are presented and discussed. These chapters provide

the findings from the individual interviews carried out with participating students and it is within these chapters that the research questions are addressed and answered. Finally, Chapter 8 concludes the thesis by summing up the main findings and providing overall conclusions. This chapter also includes a discussion of the implications of the study for physics students and educators and recommendations for further work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

As outlined in Chapter 1, the central questions in this study are concerned with the variations in students' approaches to problem solving and in their conceptual awareness. This study draws on many of the findings from previous physics education research, which has been ongoing in the United States since the late 70's and a little more recently throughout Europe and Australasia (for example see: McDermott & Redish, 1999; Hsu *et al.*, 2004; Heron & Meltzer, 2005). It became apparent to members of the academic physics community that certain naïve conceptions, with regard to physics, were common among students from a wide variety of academic backgrounds. Furthermore, conventional instruction does little to influence this naïve framework and students, who could perform well in traditional examinations, do not necessarily have the ability to qualitatively apply their knowledge to real world situations or problems. Lecturers had long been aware that much of the physics material was difficult for students to comprehend but the extent of the problem was not really recognised until physics educators began to conduct systematic investigations and document the results (McDermott, 1984). Many of these systematic studies examined how students learn physics and investigated the structure of their conceptual knowledge.

The Physics Education Research Group in DIT was initially modelled on the University of Washington Physics Education Group, particularly in terms of the research methodologies and literature that informed the research. As the research progressed I endeavoured to review all of the pertinent and relevant literature within the field. This chapter therefore seeks to provide a succinct review of the relevant literature, including a review of current practices in physics education research. Section 2.2 provides a short history of the epistemology of physics education, while section 2.3 provides a review of various perspectives on students' cognitive knowledge structure. These sections are included in the thesis because I believe a discussion of physics education research in the current climate would be incomplete without them. Section 2.4 is a review of empirical studies carried out to investigate student difficulties in mechanics and focuses on studies which have had a significant impact on research in this area. Section 2.5 examines research in the area of problem solving with an emphasis on research which explores the relationship with conceptual knowledge, while section 2.6 is an overall summary of the chapter.

2.2 History of Physics Education

Since 1965 (Arons, 1965) many physics educators have been questioning the effectiveness of their teaching on physics classes. They began to realise that physics instruction could no longer be about reproducing themselves, that is, physicists producing more physicists (Redish, 1994). Historically the students who studied physics were interested in and excited by the subject and would, in turn, be the next professional physicists. However, as higher education became more accessible to all, for many students in their classes physics was merely a compulsory element of an entire course of study.

Even so, physics education has remained relatively unchanged for over fifty years (Knight, 2002; Redish, 2003) and like many other disciplines it has tended to predominately use pedagogical approaches associated with the learning theory that emanated from behavioural psychology (Skinner, 1968). That is, the approaches have tended to be teacher-centred and for the most part, the priority within a physics course has been to transmit the ‘correct’ information to the students (Redish, 2003). Within this behaviourist perspective there is no interest in the cognitive mechanism that may be used by an individual to learn a process, nor is there an interest in whether the process learned made any sense to the individual and hence if they could use that knowledge in a different context. Mestre (2001) suggests that the behaviourist approach could be better described as training rather than educating.

However, physics education research has developed rapidly over the past forty years and the shortcomings revealed by much of this research have become more apparent with the

changes in student profile, due to things such as mass education, diversity, competition and information technology (McDermott, 1991). One possible cause for these shortcomings may lie in the suggestion that traditional physics education tends to rely on the assumption that systematically and repetitively solving relatively simple algorithmic problems will develop in students an understanding of the physics concepts and principles, as well as an appreciation of the role they play in solving problems (McDermott, 1991; Leonard *et al.*, 1996), which is evident in the way that standard physics textbooks are presented (for example see: Young *et al.*, 1999; Wilson & Buffa, 2002). Research findings from many different studies have demonstrated that problem solving by itself does not develop a deep understanding of concepts and principles, even though some students can often become proficient problem solvers by developing the ability to solve these problems through recognition of when to use an appropriate equation (for example see: Clement, 1982; McDermott, 1984, 1991; Bowden *et al.*, 1992; Hestenes *et al.* 1992). Many studies have revealed that students, who could easily solve standard textbook problems, were often unable to relate the results to other, more complex situations (for example see: Trowbridge & McDermott, 1981; McDermott *et al.*, 1987; Ambrose *et al.*, 1999; Kim & Pak, 2002).

Furthermore, research has shown that there are often significant differences between what an instructor thinks students have learned in a physics course and what the students may have actually learned (Taber, 2001). As McDermott (1991, pg 303) points out:

What the instructor says or implies and what the student interprets or infers as having been said or implied are not the same.

Another shortfall of the behaviourist approach to physics instruction arises from the tendency to teach with the attitude that students are 'blank slates'. Students are 'given' the information and are then required to repetitively solve problems in order to develop conceptual understanding. However, results from physics education and cognitive research show that students begin a physics course with their own conceptual framework, developed either through their own experiences (including formal instruction) or through 'common sense' (for example see: Halloun & Hestenes, 1985a, 1985b; Redish *et al.*, 1998; Redish 2003). Students who enter a classroom have generally been constructing knowledge for some years and if that classroom is a lecture theatre in third level education the students will probably have constructed a good deal of knowledge, both erroneous and correct. This view of learning is called constructivism which has its roots in the ideas of Jean Piaget (1970; 1972) and, according to Tuminaro & Redish (2005), it is the dominant paradigm in modern educational theories which certainly seems to be the case in the United States. Constructivism takes the point of view that learning is a process in which the learner actively constructs the knowledge they possess and that the knowledge they already possess significantly affects their ability to learn new knowledge (Glaserfeld, 1991; 1995). Leonard *et al.* (2002, pg 340) outline the premises of (psychological or radical) constructivism for pedagogical purposes as follows:

- *students have an established world view, formed by years of prior experience and learning;*
- *even as it evolves students' world view filters all experiences and affects all interpretations of subsequent observations;*

- *students are emotionally attached to their world views and will not give them up easily;*
- *challenging, revising and restructuring one's world view requires much effort.*

It should be noted here that constructivism has many forms in science education today. It has been used in a variety of ways and means different things to different researchers. A thorough discussion of constructivism and social constructivism is provided in Chapter 3. However, it is this shift from a behaviourist to a constructivist perspective to learning, as outlined above, which has led to breakthroughs in cognitive studies which focus on how people understand and learn. According to Redish (1994, pg 797) “cognitive scholars started to make real progress when they began to be willing to formulate how people were thinking in terms of mental patterns or models that could not be directly observed or measured”. Students’ mental models will be discussed in the next section, but one of the most important elements of this shift in the view of learning is that it has highlighted the need to change from teacher-centred instruction to student-centred learning (Rogers, 1983). The emphasis in a student-centred approach is on the student and specifically what the student is learning (not on what the teacher is covering or transmitting), what the student knows when they begin and how they interact with the learning environment and content (Redish, 1994). In a student-centred learning environment the principle role of the lecturer has changed from transmitting information to establishing and supporting learning environments which enable the student to challenge and test their world views.

2.3 Definition of terms

Before continuing to discuss studies from the literature about student difficulties with the conceptual nature of physics, it is necessary to define what is meant by the words *concept*, *conception* and *misconception*.

2.3.1 What is a concept/conception?

As with most aspects of physics education research the term *concept* has been used in many different forms and has been taken to mean many different things. In his Millikan Lecture, Reif (1994) states that concepts and principles are the basic building blocks of scientific knowledge and that it is the ability to interpret the scientific concept unambiguously that is a requirement for using the concept in a coherent manner. He clarifies this by explaining that “interpreting a concept means identifying or generating the concept in any particular instance” (pg 18). In addition the interpretation requires the ability to properly describe the entire component elements involved with that concept.

Dykstra *et al.* (1992) describe the term *conception* as a fundamental belief held by an individual about how the world works, which they use to explain something in a variety of different situations.

diSessa and Sherin (1998) discuss the difficulties of defining a concept (as held by an individual) and the implications that this lack of definition has had on previous research involving conceptual change. They introduce a theory of one type (out of many possible types) of concept called a *coordination class*. A coordination class consists of “readout strategies that organise sensory information and which activate a causal net of ideas that guide one’s thinking in a given situation” (Wittmann, 2006, pg 2). Redish (2004) summarises a *readout strategy* as a set of resources through which sensory information is translated into meaningful and processable terms and a *causal net* as a set of relevant inferences about the relevant information and their context-dependant associations. Hammer *et al.* (2004) argue that a conception is the basic unit of cognitive structure but that *phenomenological primitives* (explained in detail in section 2.4.2) and coordination classes can be attributed to cognitive structures at other levels which may be activated depending on the context.

However, Marton and Booth (1997) describe a *conception* as something which is related to how an individual’s awareness is structured. They use the term conception as synonymous with ‘ways of experiencing’, ‘ways of comprehending’ and ‘conceptualising’ and do not interpret these in the cognitive sense but in the experiential sense. For the purposes of my research this is what I view a conception to be because I am exploring students’ *experience* of particular aspects of physics and this will be described in more detail in Chapter 3.

2.3.2 What is a misconception?

Mestre (2001) describes a *misconception* as a preconception which is in conflict with scientific concepts. David Hammer (1996, pg 1318) summarises the core properties of these conceptions, which are often referred to in the literature as “preconceptions”, “alternative conceptions” and “misconceptions”, and he states that the core idea is of *conceptions* that:

- *are strongly held, stable cognitive structures;*
- *differ from expert conceptions;*
- *affect in a fundamental sense how students understand natural phenomena and scientific explanations;*
- *must be overcome, avoided, or eliminated for students to achieve expert understanding.*

It is this term ‘misconception’ however, that has come into dispute in recent education studies and although it is standard to accept that students enter courses with conceptions that differ from scientists’, a number of alternative theoretical models of student thinking have been presented (these are discussed below).

2.4 Different perspectives on knowledge structure

Over the last three decades educational researchers, cognitive psychologists and cognitive scientists have hypothesised about the cognitive constructs of students' knowledge structure and a number of theoretical models of human cognition have been explored in detail (Bao & Redish, 2006). At least three popular theoretical models of student thinking in physics have emerged; the first being the large scale *alternative conceptions* or *misconceptions* model (Caramazza *et al.*, 1981; Carey, 1986; Chi, 1992; Vosniadou, 1994), the second is the small grain size *knowledge-in-pieces* model (Mistrell, 1992; diSessa, 1993) and the third, which is the *resource model*, is based on neuro-, cognitive- and social-science (Hammer *et al.*, 2004; Redish, 2004; Bao & Redish, 2006; Sabella & Redish, 2007). The major tenets of each of these models will be discussed in the following sections, along with the implications of each one for physics education research.

2.4.1 The alternative conceptions model

This theory of knowledge has reiterated research from cognitive psychology indicating that for students to develop an understanding of the conceptual nature of physics, education must first start with their prior conceptions (Roth, 1990). These prior conceptions are said to be internally inconsistent and remarkably resistant to change and conventional instruction makes almost no difference to a student's conceptual beliefs (Halloun & Hestenes, 1985a). According to these researchers, the teaching approach must allow for

students to restructure their own understanding by first seeing where, when and why their conceptions fail, a process called ‘perturbation’ from the constructivist learning theory (Glaserfeld, 1989). Only after this perturbation can students start to build up a new and correct understanding. That is, in order for students to learn, they must change their mental state or undergo *conceptual change* (Posner *et al.*, 1982; Chi, 1992; Vosniadou, 1994; 2004; Chi, 2008).

Conceptual change theory can in part be traced to Piaget, and Glaserfeld (1989, pg 122) suggests that “the learning theory that emerges from Piaget’s work can be summarised by saying that cognitive change and learning takes place when a scheme, instead of producing the expected result, leads to perturbation, and perturbation, in turn, leads to accommodation that establishes a new equilibrium”. Briefly this means that learning occurs when a student’s naïve world view is challenged by an opposing view. This then leads the student to a situation in which their old understanding is challenged and no longer works and they begin to accept the opposing view because it has now proven to be more successful. Posner *et al.* (1982) followed by McCloskey (1983) described students as having alternative frameworks which needed to be replaced by correct scientific views through the process of conceptual change. The important component of this process meant that if students had to choose between competing conceptions, the new conception had to be plausible, fruitful and intelligible (Posner *et al.*, 1982). For many years this theoretical framework became the dominant paradigm for guiding research in science education. However, this framework has evolved since then into the current view of conceptual change, described below.

Conceptual change theorists claim that individuals establish a naïve framework of physics very early in life which forms the basis of that individual's ontology (conceptions of reality) and epistemology (nature of knowledge) (Vosniadou, 1994). This ontology and epistemology can then function as constraints on the knowledge acquisition process which can affect new information and the way in which it is interpreted (Vosniadou, 2003; 1994; Stathopoulou & Vosniadou, 2007). Vosniadou (1994, pg 46) claims that "misconceptions are viewed as students' attempts to interpret scientific information within an existing framework theory that contains information contradictory to the scientific view". Further, Vosniadou (2004, pg 446) argues that misconceptions are sometimes created when new knowledge "is added to an incompatible knowledge base". Chi *et al.* (1994) suggest that concepts are divided into ontological categories and although there are different types of conceptual change, the most difficult form occurs when a concept is reassigned from one category to another. They suggest that there are three primary ontological categories; matter, processes and mental states (where a mental state would have the ontological attributes of an idea), and these are then divided into subcategories. They argue that misconceptions arise when a student assigns a concept to an ontological category to which it does not belong. Specifically the ontological category that a concept belongs to in a student's mind must be changed from a non-scientific category to a correct scientific category. For example Chi *et al.* (1994) suggest that many students categorise concepts such as force as a kind of matter when in fact they should be categorised under a subcategory of process. Chi (2005) claims that in order for students to learn, they may have to be made aware that they must shift the to-be-learned concept from one ontological category to another and that instruction should focus on building these ontological categories.

Dykstra *et al.* (1992) state that in order for conceptual change to occur students' alternative conceptions must be identified and they furthermore aim to represent these conceptions as structures in the form of *conceptual maps*. Conceptual maps represent the network of the knowledge states of students and as each map represents a particular state of knowledge, the transition from one map to another represents conceptual change. One of the main tenets of the theory described above is that naïve, novice, concepts should be revised or replaced in order for the student to develop expert scientific knowledge.

Although there is still much ongoing discussion about the fundamentals of conceptual change (vastly more than has been provided here, for a previous review see Tyson *et al.*, 1997), the idea that certain 'misconceptions' about the physical world are common among students entering third level education, has been the basis for much research on student understanding in physics (Clement, 1982; Gunstone, 1987; McDermott, 1991; Hake 1998; Kim & Pak, 2002; Knight 2002).

2.4.2 Knowledge in pieces

One criticism of the validity of the misconception perspective came from Smith *et al.* (1993), who also employed the constructivist tenet to argue that if students construct new understandings out of their current knowledge, then there must be certain aspects of their current knowledge that are useful for that construction. Whereas misconception theorists use the constructivist tenet to argue that these naïve conceptions must be confronted and replaced, Smith *et al.* discuss knowledge reorganisation and refinement. They state that

implicit in the view that misconceptions must be replaced is the assumption that they play no productive role in eventual expert knowledge and therefore there are no negative consequences when they are removed. These researchers emphasise strongly how the misconceptions perspective conflicts with the constructivist theory in many fundamental ways. Smith *et al.*'s (among others, see e.g. Minstrell, 1992) criticisms of misconceptions lead many researchers to rethink their positions on the theory of student knowledge and on classic conceptual change (Stathopoulou & Vosnaidou, 2007). Smith *et al.* (1993) introduce the principle of 'knowledge in pieces', in which the central theoretical assertion is that "knowledge [is] viewed as a complex system of numerous elements" (pg 149).

Coinciding with this study, Andrea diSessa (1983; 1993) developed an account of students' prior intuitive knowledge as discrete pieces called *phenomenological primitives*, or p-prims. diSessa suggests that students develop these p-prims throughout their lives to make sense of their physical world, with a typical example of this being a "continuing force is needed for continuing motion". diSessa (1993, pg 108) makes two central claims in his 'monograph', the first of which is that the naïvely developed sense of how things work (sense of mechanism) "does not come close to the expert's in depth and systematicity" and the second is "an epistemological claim that the development of scientific knowledge about the physical world is possible only through reorganised intuitive knowledge". These p-prims are elements of an individual's cognitive knowledge structure which are activated in certain circumstances. They are not necessarily correct or incorrect, nor are they stable structures. They are described as small knowledge structures which are often self-explanatory and they act (or are cued) by being recognised and are therefore sensitive to context. Instead of replacing these knowledge elements with appropriate structures, development toward

expert understanding involves modifying their activation conditions (Hammer, 1996). An example of this would be the “force as a mover” p-prim and the subsequent development toward understanding that an object pushed *from rest* will move in the direction of the push. diSessa (1993) speculates that many ‘misconceptions’ may come from students using p-prims outside their range of valid applicability. While describing the principles for identifying p-prims, diSessa claims that his approach is the opposite of misconceptions research in that misconceptions research never analyses “correct” intuitions and likens his analyses to phenomenographic analysis. Further examples of p-prims are “ohm’s p-prim” which indicates the need to use more force to overcome added resistance; “continuous push”, which is related to “force as a mover” but indicates a persistent intention which causes motion e.g. continuously pushing a cup across a table; “dying away”, representing motion (and other properties) eventually dying away; “overcoming”, a p-prim which implies that one force or influence wins over the others. An important aspect of the p-prims model, and another point of departure from the misconceptions perspective, is that students are not consistent in their use of p-prims and their activation is sensitive to the particular context in which they are used.

A similar set of knowledge elements has been presented by Minstrell (1992); these are called *facets of knowledge* and are described as primitives in context. Facets describe the common ways in which students respond to questions that they are confronted with. Full lists of facets are available online (Minstrell, accessed 2008). Examples of facets are the “motionless equals no force” in which there is no force when two people push against each other or the “bigger equals more force” facet where a truck would exert more force on a car in a collision.

One of the major tenets of this theory of knowledge is how these intuitive elements of knowledge can contribute to and can be further developed into an expert's knowledge. Although both of the models described above have been widely accepted and have contributed to the field of physics education research, some researchers believed that both the alternative conceptions model and the knowledge in pieces model could be expanded upon and the resulting model is described below.

2.4.3 Resources model

Recent research into the neuro-cognitive structure of human knowledge has led to the resource model of student thinking (Hammer, 2000). This refers to basic elements of knowledge available to students thinking about a physics problem. Sabella & Redish (2007, pg 1018) define a resource as “a basic cognitive network that represents an element of student knowledge or a set of knowledge elements that the student tends to consistently activate together”. These basic elements could be p-prims or facets and the set of knowledge elements activated together could be what has been termed a ‘misconception’. This model of viewing student knowledge is relatively new and results from not only physics education research but also behavioural studies, neuroscience and cognitive science. The resource model does not contradict either the alternative conceptions model or the knowledge in pieces model, as it aims to build upon both these models to produce a coherent theoretical framework for modelling students' knowledge and reasoning. David Hammer (2000, pg. S58), one of the pioneers of the proposal of student resources, suggested that the study of resources could lead to a “better comprehension of (1) the

productive aspects of student knowledge and reasoning, the raw material from which they may construct a physicist's understanding, and (2) the underlying dynamics of the difficulties and misconceptions students often have in that construction". Edward Redish (2004, pg 4 - 7) outlines a number of principles resulting from neuroscience that have been used to build an understanding of mechanisms which trigger aspects of human behaviour.

The first five principles are:

1. *All phenomena are describable as arising from the fundamental physical objects and laws that we know.*
2. *All cognition takes place as a result of the functioning of neurons in the individual's brain.*
3. [Models are constrained by a number of] *Neuronal foothold principles.*
4. *There is a real world out there and every individual creates his or her own internal interpretation of that world based on sensory input.*
5. *New knowledge is built on a base of existing knowledge by building new links and suppressing old ones.*

The resources approach has therefore been described as a neurological translation of the principle of constructivism, in this case fine-grained constructivism (Redish, 2004). Results from cognitive studies and neuroscience have indicated that networks of connected neurons represent cognitive elements of knowledge and memory. When someone uses an element of knowledge in a particular network neurons are activated together. New networks are formed through synapse growth when associations are built among neurons. Therefore learning occurs when new synapses grow due to changing the topography of existing

networks (Sabella & Redish, 2007). These, (seemingly) irreducible, associated knowledge elements make up resources and the activation of a knowledge element or resource may lead to the activation of a related set of resource elements and this has been termed a *pattern of association* (Redish, 2004). A *mental model* is the name given to “a robust and coherent knowledge element or strongly associated set of knowledge elements” (Bao & Redish, 2006 pg 3). These researchers state that a misconception could be viewed as reasoning involving a mental model which has elements that conflict with an expert’s and that appear in a given population with significant probability. Interestingly Keith Taber (2008) also proposes a model of human cognition, which he terms the synthetic model, which accommodates both the alternative conception model and the knowledge in pieces model. He suggests that individuals’ knowledge is represented in the brain as a conceptual structure and that they may use stable conceptions or primitives depending on the situation and context in which they are called for. Taber’s (2008 pg 1036) model has a number of major components; *perception, conscious and unconscious thinking; ‘genetic’ predispositions built into the cognitive apparatus; conceptual structures stored in memory (i.e. represented in cognitive structure); development and learning.*

2.4.4 Summary

Although the models of student knowledge structure presented above have contributed vastly to research investigating student learning, they do not discuss the variations in students’ understanding from the students’ point of view. Yet another theory of knowledge

structure is now introduced and this theory does not posit the cognitive constructs of individuals but discusses human awareness as experiential. The main premise of this theory is that learning is experiential and is based upon discernment and variation (Marton & Booth, 1997). This is the premise upon which this work is based and the theoretical and methodological assumptions associated with this structure of awareness are discussed in detail in Chapter 3.

In this thesis I aim to develop categories which describe a set of students' experiences, approaches and conceptions of mechanics. This work is not based on the alternative conceptions model, nor is it based on the discrete knowledge in pieces model; it is based on a phenomenographic model (which will be described in detail in Chapter 3, section 3.4), which assumes that students' conceptions and approaches vary in a limited number of ways and that these ways are internally related to each other and are constituted within the students' experiences of the world. For the purposes of this study, I will refer to students' understanding of physics as conceptual knowledge, while bearing in mind that although a student may have a somewhat incorrect model of a concept, it is the variation in this conceptual knowledge that is pertinent to the study. The use of the term conceptual knowledge here is not coincidental, as I am defining knowledge as the confident understanding of concepts with the ability to use them for a specific purpose. While conceptual awareness refers to the conceptualisation of that knowledge.

2.5 Empirical studies of students' understanding of mechanics

As previously mentioned, a vast amount of physics education research studies have been carried out in the past 30 or more years which have investigated students' difficulties with the conceptual nature of physics. Although there is much discussion about the type of difficulty experienced and how the student experiences that difficulty, the research has contributed a great deal to the field of physics education and will not be neglected in this literature review. The review begins with a description of some of the early investigations which were carried out by the Physics Education Group in the University of Washington; the motivation for this is that the work carried out there strongly influenced my research. The review then continues with a description of numerous other studies investigating student difficulties in mechanics, which have also influenced and informed the research presented here.

2.5.1 Physics Education Group, University of Washington

The Physics Education Group in the University of Washington (PEG in UW) take a constructivist approach to student learning, believing that “all individuals construct their own concepts, and the knowledge they already have....significantly affects what they learn” (McDermott, 1991, pg 305). The criterion the group uses to assess understanding is the ability of the students to apply their knowledge successfully to real systems or situations. Therefore, to collect their data they carry out their research by actively engaging

the students in individual ‘demonstration interviews’. These individual demonstration interviews focus on real objects and events, and allow the interviewer to examine a student’s ability to make connections between the physical world and its algebraic and graphical representations (Lawson & McDermott, 1987). Throughout the first decade of their research, attention was mainly focused on student difficulties in mechanics. Two in-depth studies investigating student understanding in kinematics (Trowbridge & McDermott, 1980; 1981) examined the ability of a range of students to apply the concepts of velocity and acceleration in interpreting simple motions of real objects. The aim was to identify specific problems in kinematics and gain insight into possible kinematical origins of difficulties with dynamics.

The first of these studies involved ‘Speed Comparison Tasks’ (Trowbridge & McDermott, 1980) in which students were presented with demonstrations of two motions, and were asked to identify if and when the speeds of two balls were the same. It was clear from the student responses that the students were confusing speed and position. The term confusing used in this context refers not to a confused state of mind but, for example, the use of position to answer a question on speed. Out of all the students interviewed in both pre- and post-instruction interviews, about one-fifth still confused the concepts of speed and position on post-instruction interviews. As reinforcement to the interviews and to further probe the students’ understanding, the researchers administered a number of written questions in regular course examinations. To answer these questions correctly the students needed to have both a conceptual understanding and “a special kind of reasoning ability” i.e. the ability to explain their process of understanding. In answering these questions some of the students spontaneously drew graphical representations but on the whole, it was observed

that “the graphical skills acquired previously by students (were) often not incorporated into their understanding of instantaneous velocity” (McDermott *et al.*, 1987, pg 509). This matter was further probed by the research group in another study, which involved investigations into student difficulties in connecting graphs and physics (McDermott *et al.*, 1987). They compared the answers of a self-selected group (volunteers) to those of a group who were interviewed as part of their instruction. They found no significant difference in performance between the two groups and they discovered that there was little or no learning effect for those students who partook in both pre and post-course interviews.

The second of these two studies used acceleration comparison tasks (Trowbridge & McDermott, 1981). Again the students were asked to observe and compare the motion of two balls having different accelerations. Success on this task meant that the student used a valid procedure for comparing accelerations, besides substituting into a kinematical formula. The researchers found that students used a number of procedures to compare the accelerations, with only two of the procedures showing a qualitative understanding of acceleration as the ratio of the change in velocity to the change in time. The various other procedures used included a non-kinematical approach, where the students concluded that the balls had the same acceleration because the slopes of the paths were the same. Other procedures showed confusion between position and acceleration or between velocity and acceleration. Another procedure involved discrimination between velocity and change in velocity but neglected the corresponding time interval. Of all the students interviewed about one third still confused the concepts of velocity and acceleration on post-instruction interviews and in the introductory level populations studied, about two thirds of the students did not use ratios to compare accelerations in post-instruction interviews. One

conclusion that the researchers drew from these two studies was that “active intervention is necessary for overcoming confusion between related but different concepts” (Trowbridge & McDermott, 1981, pg 253). The group then used the results of the above research on student understanding to guide the development of a conceptual approach to teaching kinematics (Rosenquist & McDermott, 1987). The group found that instruction based on observation of actual motion could help students develop a qualitative understanding of velocity and acceleration and to distinguish concepts of position, velocity and changes in velocity and acceleration from one another.

At the same time the group carried out a study investigating student understanding of the concepts of impulse and work and the relationship of these concepts to changes in momentum and kinetic energy (Lawson & McDermott, 1987). Again in this mainly descriptive study the method of research was the individual demonstration interview and the interviews were carried out for students who had already completed instruction in the area.

Overall the researchers found that many students “experienced considerable difficulty in a straightforward application of the impulse-momentum and work-energy theorems to the actual one-dimensional motion of an object under constant force” (Lawson & McDermott, 1987, pg 816). It became clear that for students to apply these relationships to real world situations they would require knowledge at a deeper level than simply memorisation of the theorems. While discussing implications for the theorems the researchers concluded, “fundamentally important features of concepts that are not easily visualised will be missed if they are presented verbally, whether by textbook or lecture” (Lawson & McDermott,

1987, pg 817). They argue that students need experience in interpreting the formal relationships of physics in a variety of different contexts and under different conditions. The group continue to investigate students' understanding of kinematics and in a recent study they investigated not only introductory students' understanding but also graduate students' of two-dimensional kinematics. They found that in this case even graduate students had difficulty with velocity and acceleration, particularly with vector operations (Shaffer & McDermott, 2005). The work carried out by PEG in UW has informed the treatment of kinematics in innovative curricula in the US and across the world (Physics by Inquiry PbI, McDermott and the PEG at UofW, 1996; McDermott *et al.*, Tutorials in Introductory physics TiLP, 2002).

2.5.2 Sample of studies concerning conceptual understanding in mechanics

From the late 1970s onwards there have been numerous studies investigating student difficulties in mechanics. Many of these studies, conducted all over the world, involved investigating and identifying students' preconceptions or misconceptions (to name but a few, Aguirre & Erickson, 1984 in Canada; Finegold & Gorsky, 1991 in Israel; Gunstone & White, 1981; Gunstone, 1987 in Australia; Caramazza *et al.*, 1981; Clement, 1982; Peters, 1982; Halloun & Hestenes, 1985a; Hestenes & Halloun, 1995 in the US; Viennot, 1979; Saltiel & Malgrange, 1980; Watts, 1983 in Europe). The results of these studies were a taxonomy of students' difficulties in kinematics and dynamics. John Clement (1982)

introduced the preconception “motion implies force” to which he attributed three main characteristics; continuing motion implies a force, one force overcomes another and forces ‘die out’ or ‘build up’ (although this preconception had been observed in previous studies for example see Champagne *et al.*, 1980). However, these characteristics of the stable preconception have since been labeled phenomenological primitives (diSessa, 1993) and context dependent facets (Minstrell, 1992). Aguirre and Erickson (1984) (and subsequently Aguirre (1988) and Aguirre and Rankin (1989)) found that students had stable alternative conceptions of vector kinematics and that up to 50 % of these students maintained these naïve conceptions after formal instruction in mechanics. A study carried out in 2003 (Nguyen & Meltzer, 2003) confirmed that students retained conceptual difficulties with vectors after formal instruction in the area. For other studies involving student difficulties and understanding of vector concepts see Knight, 1995; Flores *et al.*, 2004 and Shaffer & McDermott, 2005. Halloun and Hestenes (1985a) produced results which suggested that students had a number of ‘common sense concepts’ regarding motion both prior to and after formal instruction (their work is described in more detail below in section 2.5.2). While there are still numerous studies being carried out investigating student difficulties in mechanics (for example see Rimoldini & Singh, 2005; Poon, 2006; Sharma & Sharma, 2007) much research within the physics education research community has now shifted from exploring these stable alternative conceptions to finer grained ‘primitives’ or ‘resources’ as described above (for example see, Hammer, 2000; Bao *et al.*, 2002; Smith & Wittmann, 2007) and many recent studies focus on the cognitive constructs of student thinking and learning (for example see, Bao & Redish, 2006; Wittmann, 2006; Podolefsky & Finkelstein, 2007).

There have also been numerous studies carried out which do not specifically focus on the difficulties that students have in understanding the concepts in mechanics but rather aim to describe the various ways in which these students understand these concepts (for example see: Dall'Alba *et al.*, 1989; Johansson *et al.*, 1985; Millar *et al.*, 1989; Prosser & Millar, 1989; Bowden *et al.*, 1992; Dall'Alba *et al.*, 1993; Ramsden *et al.*, 1993; Walsh *et al.*, 1993; Sharma *et al.*, 2004). These studies produce sets of hierarchical categories which describe the variations in the ways in which students experience the concepts in question and through the hierarchical nature of the categories developments in teaching and assessment practices may be made in order to move students from lower levels of understanding to higher levels.

For example Millar *et al.*, (1989) carried out a study which investigated first year university students' conceptions of force and motion using data from responses to a question on velocity. The question was "A car is driven at a high constant speed along a straight line on a highway. What forces act on the car to let it travel like this?" The researchers constituted three qualitatively different ways of conceptualising force and motion within that context. These qualitatively different ways, which form a logical hierarchy according to the researchers, are:

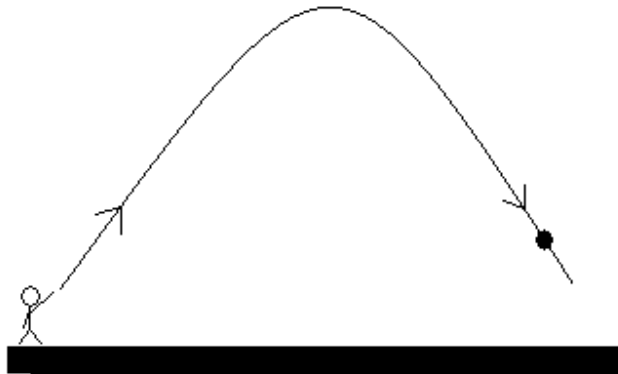
A. The car has a constant velocity because the *internal* force due to the engine in the direction of motion is *greater* than the *external* frictional force between the tyre and the road in the opposite direction.

B. The car has a constant velocity because the *internal* force due to the engine in the direction of motion is *equal* to the *external* frictional force between the tyre and the road in the opposite direction.

C. The car has a constant velocity because the *external* frictional force between the tyre and the road in the direction of motion is *equal* to the *external* frictional force due to air resistance in the opposite direction.

The first conception they attributed to an Aristotelian view with the second being a partially correct Newtonian view and the last corresponding to a correct Newtonian view of force and motion.

As part of a large-scale research project, researchers from Australia, UK and Sweden collaborated to produce phenomenographic categories describing the variations in students' understanding of mechanics. A number of students were invited to participate in individual interviews in which students were asked to respond to a number of questions. An important point about these interviews was that students were encouraged to give full explanations of their understanding. Bowden *et al.* (1992) constituted categories describing the variations in understanding of displacement, velocity and frames of reference by analysing the data obtained from the interviews with students. Ramsden *et al.* (1993) report categories from analysis of the same set of interviews which describe the variations in students' understanding of speed, distance and time. Walsh *et al.* (1993) reported on the variations in understanding of relative speed and Dall'Alba *et al.* (1993) produced six categories which described the qualitatively different ways in which the students understood acceleration and compared these to textbook treatments of acceleration. As the latter study is most relevant to my research study, I will describe it here in some detail. Twenty-five to thirty students who participated in the study as a whole were asked to respond to a problem (seen below as Figure 2.1) which dealt with acceleration (Dall'Alba *et al.*, 1993 pg 623).



A small steel ball, thrown up in the air, follows the trajectory shown. Air resistance is negligible. Discuss the acceleration of the ball from the time it leaves the hand until it approaches the ground.

Figure 2.1: Problem presented to students in order to discover qualitatively different ways in which they understood acceleration. (Dall’Alba *et al.*, 1993, pg 623)

Although the problem was the basis for the interview, the focus during the interview was on exploring students’ understanding of acceleration by asking questions such as ‘could you explain that further?’ and ‘why does that happen?’. Having transcribed all of the interviews which dealt with this problem the researchers then carried out a phenomenographic analysis of the transcripts, which is a rigorous iterative process. Categories were thus constituted which described the qualitatively different ways in which the students understood or conceptualised acceleration, these are:

- Category Cr: Caused by gravity; rate of change of velocity
- Category R: Rate of change of velocity
- Category G: Gravity is closely linked but not causally
- Category F: Acts as force

- Category D: Differences in velocity
- Category Fgb: Forces – Acceleration due to gravity and acceleration of the ball

These categories will be discussed in more detail in Chapter 7, where I will present my own categories and relate them to the findings from this study.

Another example of this type of study was reported by Sharma *et al.* in 2004, when they investigated students' understanding of gravity in an orbiting spaceship. Again using qualitative interviews which were subsequently analysed, the researchers constituted 4 main categories describing the variations in how those students understood the concept of gravity.

2.5.3 Development of research based diagnostic tools

In the early 1980's staff in the Department of Physics in Arizona State University (namely Ibrahim Halloun and David Hestenes) became aware that conventional instruction was not taking into account the fact that students enter third level with their own 'common sense' concepts of motion (Halloun & Hestenes, 1985b). They were aware of current research in the area of physics education and found that it had, up to that time mainly focused on isolated concepts. Therefore they formed the Physics Education Research and Development group with the aim to design and implement an instrument for assessing the knowledge state of students beginning to study physics, which would include mathematical knowledge as well as beliefs about physical phenomena (Halloun & Hestenes, 1985a).

The group designed two tests, a physics diagnostic test and a mathematics diagnostic test. The former used to assess the students' qualitative conceptions of common physical phenomena in both pre and post-test form, while the latter used as a pre-test to assess the students' mathematical skills. The questions in the physics diagnostic test were chosen to highlight the differences between common sense and Newtonian concepts (the term common sense here refers to that of an individual with little formal instruction in physics relying only on personal experience) and to identify the misconceptions that had been discovered by previous researchers. The test, administered in various forms to over one thousand college students in introductory physics courses, initially required written answers. The most common answers were then collated to form multiple choice questions, which made the finished product, the mechanics diagnostic test, easier to grade. Extensive measures were taken by the group to validate and examine the reliability of the test as the tests were given to professors, graduate students and introductory physics students to ensure that all understood the questions and optional answers. From interviews with a sample set of students to establish the reliability of the tests and they found that almost all students gave the same answers in the interviews as in the written test. In addition the students were not easily swayed from their answers when questioned, which implied that the answers reflected stable beliefs. The group concluded that "a student's score on the diagnostic test is a measure of his qualitative understanding of mechanics" (Halloun & Hestenes, 1985a, pg 1048). The mathematics diagnostic test was designed to assess mathematical skills known to be important in introductory physics and again the initial version of this test required written answers which were then used to make up the multiple choice questions. The group noted that incorrect answers were not random but indicated common misconceptions and that those errors could tell something about the way that the

students think. As with the physics diagnostic test, measures were taken to ensure the validity of the test.

The tests were administered not only to students from a number of introductory physics courses in Arizona State University but also to college physics students and high school students. The researchers correlated scores on the mathematics and physics pre-tests with course performance and found that pre-test scores were consistent across different student groups and that the tests had higher predictive validity for student course performance than all other documented variables combined. This, the researchers say “shows conclusively that the initial knowledge state measured by the two pre-tests has a significant effect on course performance” (Halloun & Hestenes, 1985a, pg 1048). When comparing pre- and post-test results, the researchers concluded that the knowledge gained by the students was independent of the instructor and that the small gain in basic knowledge was very disturbing. This, they felt, implied that the students were seriously defective in conceptual understanding and must have continually misunderstood material which was presented to them. They also found that the post-test scores correlated highly with course performance, but that these scores were also unacceptably low. The researchers feel that these diagnostic tests could be used in a number of ways, such as a placement examination to identify those students who will have difficulty with the course, as a tool to evaluate instruction or as a diagnostic test to identify and classify specific misconceptions. The group concludes that the “test results show that a student’s initial knowledge has a large effect on his performance in physics but that conventional instruction produces comparatively small improvements in his basic knowledge” (Halloun & Hestenes, 1985a, pg 1048). The

researchers claim that the test not only shows that Newtonian conceptual understanding is missing but that alternative conceptions of mechanics are firmly in place.

Having identified the need to take initial common sense beliefs of students into account in physics instruction, subsequent work by this group of investigators involved categorising these common sense beliefs for mechanics instruction (Halloun & Hestenes, 1985b). The researchers noted that these common sense beliefs should not simply be dismissed, as these beliefs were firmly held by leading intellectuals in pre-Newtonian times. Rather they should be treated as “serious alternative hypotheses to be evaluated by scientific procedures” (pg 1056). Therefore rather than being told a belief is incorrect, students are provided with sound reasoning for altering their beliefs. In this study the researchers presented some major ideas of pre-Newtonian physics as well as a report on their own observations of common sense beliefs held by contemporary students. Finally they presented a catalogue of common sense beliefs as a guide to instructional design. These common sense beliefs become more important when learning is viewed as being constructed from previous knowledge.

This group of researchers later used the information obtained from the mathematics and physics diagnostic tests to further refine these tests into more valuable resources, namely ‘The Force Concept Inventory’ (Hestenes *et al.*, 1992) and ‘The Mechanics Baseline Test’ (Hestenes & Wells 1992). The Force Concept Inventory (FCI) probes the student’s common sense beliefs on force and how those beliefs compare to Newtonian mechanics. The researchers identified six dimensions within the concept of Newtonian force and the condition that they place on complete understanding of the concept is a set of correct

answers in each dimension. The group suggest that errors on the test are actually more informative than correct answers, as they bring to light a student's misunderstanding of a particular concept and as stated previously they feel that this test can also be used as a diagnostic tool, as a placement exam or as a tool for evaluating instruction. In these applications, the test is highly effective but simply being aware of student misconceptions is not sufficient to improve the effectiveness of instruction. The researchers believe that these misconceptions must be replaced by solid Newtonian conceptions and this cannot be achieved by telling the student he/she is wrong. They also state their belief that conceptual understanding must be developed before problem-solving instruction can be effective.

Another research-based multiple-choice assessment of student conceptual understanding is the Force and Motion Conceptual Evaluation (FMCE), developed by Ronald Thornton (Tufts University) and David Sokoloff (University of Oregon) (Thornton & Sokoloff, 1998). While this inventory is similar to the FCI described above, it appears to be more statistically sound, as it uses a number of questions on each concept to cross-reference the students' understanding. The FMCE was developed in much the same way as the FCI, using results from physics education research (Thornton & Sokoloff, 1998) and carried out before and after instruction on a large number of students. As the researchers point out some of the multiple-choice questions on the inventory serve specific purposes, such as identifying students who are beginning to accept a Newtonian view and those far from consistently adopting a Newtonian view. Using open-ended, alternative questions, the researchers were successful in validating the FMCE to a very high degree, (1998, pg 345)

The agreement between the multiple-choice and open answer responses is almost 100%. Such results give us confidence in the significance of student choices.

The researchers point out that there are very few random answers on the test and with even the less common beliefs about motion being represented in the distractors (wrong answers), students almost always find an answer that they are satisfied with. I have chosen to use the multiple-choice assessment tool described here (FMCE) in conjunction with my research and this will be discussed in further detail in the following chapter.

2.5.4 Summary

As stated above, these accounts of empirical studies into student difficulties in mechanics are but a small cross-section of the work that has been carried out in the United States and around the world (McDermott & Redish, 1999). Another group of researchers who have carried out extensive research into the learning and teaching of physics is the University of Maryland Physics Education Research Group. Their work has a strong problem solving emphasis but it is very much linked to conceptual knowledge, including research on the cognitive structures that are involved in learning and their work is discussed at various stages throughout this Chapter. Research in this area has also become popular in other parts of the world, for example, a group of researchers from Australia and Europe have collaborated to carry out the phenomenographic studies described in section 2.5.2, into students' understanding of physics concepts (Bowden *et al.*, 1992; Dall'Alba *et al.*, 1993; Walsh *et al.*, 1993; Ramsden *et al.*, 1993, Sharma *et al.*, 2004). Research in Australia (Gunstone, 1987), Korea (Kim & Pak, 2002), in Israel (Finegold & Gorsky, 1991), in England (Graham & Berry, 1996; 1997), to name but a few, have all provided valuable information on how and what students learn in introductory physics.

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2.6 Empirical studies in problem solving

2.6.1 Overview of empirical studies in problem solving

While a large number of physics education research groups have carried out studies on conceptual difficulties experienced by students, fewer studies have focused on the variations in students' approaches to solving quantitative problems (Heron & Meltzer, 2005). This is surprising, as one of the principal goals of a physics course is to produce adept problem solvers who can transfer their knowledge and understanding to real world situations. An issue which has been raised by a number of physics education researchers recently is whether the community is placing too much emphasis on gains in conceptual understanding, while “sacrificing problem solving skill development” (Hoellwarth *et al.*, 2005). Having said that fewer studies have investigated interventions to improve problem solving in physics, there is still extensive literature on the subject of the problem solving abilities of students (For example; McDermott, 1984; Van Heuvelen, 1991a; 1991b; Heller *et al.*, 1992; Heller & Hollabaugh, 1992; Thacker *et al.*, 1994; Maloney, 1994; Bolton & Ross, 1997; Hsu *et al.*, 2004; Meltzer, 2005).

Many studies have shown that although students can learn to solve quantitative problems by plugging values into algorithmic equations, they may not be developing the skills necessary to transfer their understanding and solve more complex problems (Mazur, 1992; 1997; Leonard *et al.*, 1996; Reif & Scott, 1999; Kim & Pak, 2002; Redish, 2005). A

common view throughout most of this literature is that instruction should encourage students to ‘think like a physicist’ or result in a shift from ‘a novice problem solver’ to ‘an expert problem solver’. Reif and Heller (1982) discussed this view of student problem solvers by comparing and contrasting the problem solving abilities of novices and experts. Their findings showed that the principal difference between the two was how they organise and use their knowledge in the context of solving a problem. Experts rapidly re-describe the problem and often use qualitative arguments to plan solutions before elaborating on them in greater mathematical detail. Novices rush into the solution by stringing together miscellaneous mathematical equations and very quickly encounter difficulties. Physicists organise their knowledge in a very structured way and therefore can call on this knowledge when, and in the order that, it is needed. However, novice physics students do not necessarily have this knowledge structure, as “their understanding consists of random facts and equations that have little conceptual meaning” (Van Heuvelen, 1991a, pg 894). This gap between expert and novice problem-solvers has been well studied, with an emphasis on classifying the differences between students and experts in an effort to discover how students can become more ‘expert’ like in their approach to problem solving (Larkin *et al.*, 1980; Schultz & Lockhead, 1991; Priest & Lindsay, 1992; Reif & Allen, 1992; Leonard *et al.* 2002; Brand-Gruwel *et al.*, 2005). However, introductory physics students will rarely achieve this higher-level problem solving expertise during their first year in college, nor are they necessarily expected to. What is expected is that they begin to develop a coherent knowledge structure, which they can then learn to access and ‘activate’ appropriately in order to solve problems (Sabella, unpublished dissertation, accessed 2008; Sabella & Redish, 2007).

Chi *et al.* (1981) investigated the differences between how experts and novices categorise a problem and they found that experts categorised the problem based on the major physics principles to be used in the solution, whereas novices categorise the problems based on elements within the problem statement. A further study by Chi (2006) again investigated the nature of expertise and endeavoured to discover the differences between experts' and novice's representations of their knowledge.

Within much of the literature, the differences between experts and novices are discussed under the umbrella of two categories; knowledge organisation and knowledge use (Mestre, 1994). Mestre (1994) conducted a review of problem solving research with an emphasis on the cognitive aspects of learning and suggests that research has shown skilful problem solving is a result of "1) a substantial, richly cross-referenced, hierarchical organised knowledge base and 2) qualitative reasoning based on conceptual knowledge". Leonard *et al.* (1996) reported on the use of qualitative problem solving strategies in order to highlight the role of conceptual knowledge in solving problems and they comment that students should be encouraged to incorporate a qualitative 'strategy' when problem solving. Mestre (1994), among others (Hardiman *et al.*, 1989; Dufresne *et al.*, 1992; Mualem & Eylon, 2007), calls for a reform in problem solving instruction, emphasising the need for instruction to encourage qualitative reasoning.

Leonard *et al.* (2002) summarised a large proportion of this research using two tables (see Tables 2.1 and 2.2) to highlight the comparisons between knowledge characteristics and problem solving behaviours of experts and novices. Leonard *et al.* (2002) identified five

types of learning experiences in an effort to further understand students' understanding of concepts. These were

- exploring students' existing concepts;
- honing and clustering concepts;
- developing analysis and reasoning skills;
- developing problem solving skills;
- structuring knowledge in memory.

Tables 2.1 and 2.2 illustrate the differences between experts and novices in regard to the honing and clustering of concepts (second bullet point above) and developing problem solving skills respectively.

Table 2.1: A comparison of the knowledge characteristics of experts and novices.

(Leonard *et al.*, 2002, pg 393)

Expert	Novice
Large store of domain-specific knowledge	Sparse knowledge set
Knowledge richly interconnected	Knowledge mostly disconnected and amorphous
Knowledge hierarchically structured	Knowledge stored chronologically
Integrated multiple representations	Poorly formed and unrelated representations
Good recall	Poor recall

Table 2.2: A comparison of the problem solving behaviours of experts and novices.

(Leonard *et al.*, 2002, pg 389)

Expert	Novice
Conceptual knowledge impacts problem solving	Problem solving largely independent of concepts
Often performs qualitative analysis, especially when stuck	Usually manipulates equations
Uses forward-looking concept-based strategies	Uses backward-looking means-end techniques
Has a variety of methods for getting unstuck	Cannot usually get unstuck without outside help
Is able to think about problem solving while problem solving	Solving problems uses all available resources
Is able to check answer using an alternative method	Often has only one method of solving a problem

Leading on from these tables the researchers suggested the implementation of an instructional tool called *analysis-based problem solving* which develops skills that traditional problem solving activities do not. As Leonard *et al.* (2002 pg 394) suggest:

Without a strong conceptual foundation and without analysis, reasoning, and other skills, students will continue to adopt superficial and formulaic approaches to problem solving.

The characteristics of expert and novice problem solvers identified by Leonard *et al.* (2002) will be discussed in more detail in Chapter 5 in relation to findings from my research.

Several studies have also highlighted the importance of multiple representations (Dufresne *et al.*, 1997; Meltzer, 2005; Lasry & Aulls, 2007) and analogies (Podolefsky & Finkelstein, 2006; 2007) in learning to problem solve in physics. Kohl and Finkelstein (2005; 2006a) illustrated, through the use of problem solving interviews, that students' problem solving performance can strongly depend on the representational format of the problem and that students who were exposed to 'reform-style' instruction (such as Interactive Lecture Demonstrations and Peer Instruction) could develop broader skills. In a third study (Kohl & Finkelstein, 2006b) the researchers discovered that students' problem solving strategy sometimes varied with the problem representation and those students who varied their strategy often performed poorly. Lasry and Aulls (2007) recommend the use of 'hands-on' activities which require the use of verbal, visual, logico-mathematic (ability to make deductions and inferences), kinaesthetic (ability to extract information through measurements or manipulations) and social representations. They incorporated context-rich problems with a cooperative-group approach (Heller & Hollabaugh, 1992; Heller *et al.*, 1992) to measure the effect of adding multiple representations to activities. These multiple representations require an increase in *n-coding* (a term coined by these researchers, *n-coding* "is the ability to represent information mentally along multiple dimensions" (pg 1031)) from the students. A major tenet of this representation and analogy research is that expert scientists use multiple representations and analogies when describing or discussing complex phenomena due to the organised nature of their cognitive knowledge structure and therefore instruction should encourage students to use representations and analogies to aid in the development of problem solving skills.

One research group, among others, who have devoted much of their research to investigating students' different problem solving approaches is the University of Maryland Physics Education Research Group. A large portion of their foci has been on exploring the manner in which students activate (or do not as the case may be) their knowledge of mathematics in order to approach physics problems (Redish *et al.*, 1996; Tuminaro & Redish, 2004; Tuminaro & Reish, 2005; Redish *et al.*, 2006). Tuminaro & Redish (2007) describe students' use of mathematics in their approaches to problem solving in terms of the epistemic games (Collins & Ferguson, 1993) that they play while attempting to solve the problems. This work involved the categorisation of students' problem solving approaches while they worked in groups using an observational methodology. The researchers identified six epistemic games that these students played as they used mathematics to approach problem solving. These were *mapping meaning to mathematics*, *mapping mathematics to meaning*, *physical mechanism game*, *pictorial analysis*, *recursive plug-and-chug* and *transliteration to mathematics*. These 'epistemic games' will be discussed in more detail in Chapter 5 as I will be comparing them to results obtained through my own research.

2.6.2 Problem solving summary

As mentioned previously, the physics education group in Arizona State University discussed their belief that conceptual understanding must be developed before problem-solving instruction can be effective and often many studies have re-iterated this belief (for

example see: Crouch & Mazur, 2001; McDermott *et al.*, 2002; Kim & Pak, 2002). However, there are groups of researchers who believe that conceptual understanding and problem solving ability are (or should be) intrinsically linked (Heller *et al.*, 1992; Heller & Hollsbaugh, 1992). One focus of these studies is the development of context-rich problems which shift student focus from formulas to the applicability of physical concepts and principles in a given situation. Other groups of researchers believe that conceptual knowledge alone is not sufficient for adept problem solving ability (Meltzer, 2002) and that “students also need to know how and when to use that knowledge” (Sabella & Redish, 2007, pg 1017). David Meltzer (2002; 2005) has examined whether students’ conceptual learning gains correlate with their mathematical skills and, as discussed above, has investigated the effect that representational format has on students’ problem solving performance. He argues that conceptual knowledge should be assessed through the use of qualitative problems. Hoellwarth *et al.* (2005) have undertaken research that directly compares conceptual learning with problem solving ability in classes with two different methods of delivery. Hoellwarth *et al.* used both the FCI and the FMCE to measure conceptual knowledge and a number of quantitative “common” (pg 460) problems on the students’ final exams to measure problem solving ability. The group concluded “students must be taught both concepts and problem solving skills explicitly if we want students to be proficient at both” (Hoellwarth *et al.*, 2005, pg 462). Tuminaro and Redish (2007) note that although significant research has been conducted that has documented the differences between experts and novices and research has attempted to design learning environments that improve problem solving, “none of these approaches ... help us to understand how students make the transition from novice to expert. In order to make progress on these

issues we have to understand how novices and experts approach problems, and we have to have effective ways of talking about and describing the differences” (pg 2).

2.7 Chapter Summary

This chapter has examined the research reported in academic literature related to the core issues of this study. It considered the findings from physics education research, the overarching theme being, that traditional instruction in physics is not effective if the goal of instruction is to develop conceptual knowledge and produce problem solvers with the ability to conceptualise and transfer their understanding. It discussed students' difficulties with the conceptual nature of physics and outlined research in the area of quantitative problem solving. The research has suggested that further investigation into the relationship between conceptual knowledge and problem solving ability is needed and this has been reiterated recently by Paula Heron and David Meltzer in their Guest Editorial (Heron & Meltzer, 2005). Another suggestion made in this Editorial is the need for "greater emphasis on tracing students' intellectual development as they progress through the undergraduate curriculum" (pg 390). The outcome of research in physics education has been the development of several instructional methods, which have been implemented in a number of institutions around the world. These outcomes will be discussed again in view of the findings from this research study in the following chapters.

CHAPTER 3

RESEARCH DESIGN

3.1 Introduction

Chapter 2 reviewed the key issues that are pertinent to the study of student learning in physics and in particular issues relating to conceptual knowledge and problem solving ability. This chapter is concerned with how these issues might be investigated empirically in the context of this study. This research study set out to explore the variations in introductory physics students' conceptual awareness and their approaches to problem solving. Therefore the research has to be undertaken within the appropriate framework in order to answer the research questions and that framework, broadly speaking, is education research.

Creswell (2003) discusses the use of three framework elements in designing this kind of research:

Knowledge claims

Strategies of inquiry

Methods

Creswell (2003, pg 4) explains that “stating a knowledge claim means that researchers start a project with certain assumptions about how they will learn and what they will learn during their inquiry”. Therefore this chapter begins with a discussion of the assumptions with which I began this research, including the theoretical perspective in which the research is grounded. The capability to reliably answer the research questions in a study such as this is deeply embedded in the strategy of inquiry which is employed. As a strategy of inquiry, or methodology as I will refer to it, I have chosen a phenomenographic approach. I believe it is the most appropriate with which to answer my research questions based on my theoretical assumptions and this choice will be fully justified in section 3.4 of this chapter. Section 3.5 describes in detail the methods of data collection and analysis which were employed in this research and the final sections in the chapter describe the participants who took part in the study and a discussion of the ethical considerations which were present in the research. This chapter is a necessary prelude to the remainder of the thesis as it places the research data, analysis and participants within the context of the study.

3.2 Theoretical Perspective

It would be true to say that the reasons behind the choice of research methods in this study were essentially pragmatic. Indeed, when choosing the research methods I focused my attention on the research questions (as described in Chapter 1) and hence allowed myself the choice of both qualitative and quantitative methods. Grounding the research in this perspective, that is the “pragmatic stance” as discussed by Creswell (2003), would have allowed me to choose these mixed research methods and techniques and would have eliminated the need for me to commit myself to any one system of philosophy: As Creswell, suggests: (2003, pg 12)

Pragmatists believe that we need to stop asking questions about reality and the laws of nature.

However, to situate myself in the pragmatist position (Cherryholmes, 1992) would be to ignore the fact that the research questions themselves are informed by an entirely different theoretical perspective. The research questions were very much informed by my own epistemological stance and the theoretical perspective from which I set out to address the research problem. The reasons the research questions concentrate not on “fact”, but on experiences, conceptions and perceptions lie in my epistemological stance and the assumptions I bring to this research.

One of the assumptions that I am bringing to this research is that reality is neither external nor internal. Instead it is a relation between the two and therefore knowledge is not entirely constructed internally nor does it exist without being conceptualised. Svensson (1997, pg 165), while discussing the theoretical foundations of a non-dualistic ontology, observed that:

The truth of knowledge is uncertain and neither the positivistic belief in observation and induction nor the phenomenological belief in identity between thought and phenomenon are accepted.

So for this reason my research is based in the interpretivist tradition, which attempts “to understand and explain human and social reality” (Crotty, 1998, pg 66).

One researcher who is particularly associated with student learning is the Swedish educational psychologist Ference Marton, whose work focuses on how students conceive learning and how they approach learning. He and many other researchers believe that learning and therefore knowledge is not discovered, but is constituted through an internal relationship between the individual and the world (Marton 1981; 1986). This has been termed a ‘second order’ research perspective (Marton, 2000), which means instead of examining student learning or the content itself, I explored the students’ experiences of that content. The term *experience* is used here not as involvement in or knowledge of the content but in the much broader sense of how the students are aware of the content. It follows then that this research is my interpretation of students’ *experience* of physics and

from that interpretation I will achieve a better understanding of the variations in these students' conceptual awareness and approaches to problem solving.

3.3 Theoretical Assumptions

As discussed in Chapter 2 it has been appropriate for some time to think about learning as being constructed through prior experiences, perceptions and approaches rather than being discovered (Prosser & Trigwell, 1999). However, this view, like most others in education research has evolved over time.

The constructivist approach to learning is based on a combination of a subset of research within cognitive psychology (Ausubel, 1968; Piaget, 1972; Bruner, 1990) and a subset of research within social psychology (Vygotsky, 1978). From a cognitive perspective the learner selects and transforms information, constructs hypotheses, and makes decisions, relying on a cognitive structure to do so. From an individual constructivist approach knowledge is constructed internally and tested through interaction with the outside world (Glaserfeld, 1995). From a social constructivist perspective cognitive functions originate in, and must therefore be explained as products of, social interactions and learning is not simply the assimilation and accommodation of new knowledge by learners but the process by which learners are integrated into a knowledge community (Vygotsky, 1978).

Traditionally, physics education researchers claim to have taken a constructivist approach to the learning process believing that “all individuals must construct their own concepts, and the knowledge they already have....significantly affects what they learn” (McDermott, 1991 pg 305). Tuminaro and Redish (2005) suggest that constructivism is the dominant paradigm in modern educational theories. The use of the term *paradigm* here is not

coincidental as constructivism in science education is often viewed as a perspective from which to approach learning and teaching (Tobin & Rippins, 1993; Tobin, 2003). However, radical constructivism (Glaserfeld, 1989, 1992) is an epistemology, a theory of experiential knowledge, experiential knowledge being knowledge gained through experience.

Donald Wink (2006) discusses the connection between “pedagogical” constructivism and “epistemological” constructivism for research in chemistry and generally for science. He states that neither has been significantly defined and he proceeds to provide his own definition (pg 113):

Pedagogical constructivism views the individual learner as the only location where knowledge is generated and maintained. Knowledge is bound to the person who generates it. And a person’s knowledge always depends on how a person approaches a learning experience, what he or she actively does during the experience, and how the resulting knowledge is integrated into what the person knows. Interactions with others and with nature may influence the learner’s construction of knowledge, but neither reality nor community can compel knowledge formation. The learner, the teacher, and the educational system shape the content and the process of what is learned in fundamental ways.

Epistemological constructivism views knowledge as something that individuals and groups construct from their own choices, perhaps in interactions with non-humans. Acceptance, not “truth” is the key step in making something knowledge. Even well-established knowledge requires a

human element to maintain it as knowledge over time. Things are “known” in different ways depending on context and need, and there is no principled reason why multiple knowledges will ever be unified. Premise, history, and sociological factors such as gender and ethnicity are always factors in knowledge.

Duit (1996, pg 41) outlined three key principles of the radical constructivism epistemology: 1) “knowledge is not passively received but it is built up by the cognizing subject”, 2) “the function of cognition is adaptive and enables learners to construct viable explanations of experiences”, and 3) “the process of constructing meaning is always embedded within a social setting of which the individual is part”. A number of criticisms of the constructivist approach have arisen from the science education community (for example see: Matthews, 1993; Soloman 1994; Suchting, 1992; for reviews see Duit, 1993; Taber, 2006). However, as Duit (1996) points out, the key principles seem not to be questioned by the critiques. The criticisms have generally originated from the philosophical underpinnings of the constructivist theory, with a common feature being the apparent denial of the existence of the physical world - although this is untrue, as Glaserfeld (1992) does not deny the existence of external reality but denies the possibility of attaining definite knowledge of that reality.

Another criticism arises from the view that the individual and the world are separated from each other, which Marton & Neuman (1989) suggest leads to paradoxes. Marton & Neuman (pg 36) argue that

To think ... is always to think about something and to perceive is always to perceive something. The individual's experience of the world is a relation between the individual and the world, both are presupposed. Thus there are not two separate entities (individual and world) plus a relation between them; the world-as-experienced is all there is.

Marton & Neuman clarify this by stating that although there is a 'real world out there', it is an experienced world, therefore an experience (a conception, a phenomenon etc.) is a relation between the person doing the experiencing (conceptualising) and the something to be experienced. This led to a new theory of knowledge, similar to constructivism, called "constitutionalism", which is grounded in the principle of intentionality¹ (Marton & Neuman, 1989; Marton & Booth, 1997). The fundamental nature of constitutionalism is that meaning is constituted through an internal relationship between the individual and the world. Prosser & Trigwell explain (1999, pg 13)

Learning is about experiencing the object of study in a different way, where the experience is a relationship between the person experiencing and the object experienced.

Marton (1981) suggests that there are two ways to approach questions about learning:

1. To orient ourselves toward the world and make statements about it and its reality;
2. To orient ourselves toward people' ideas or experiences of the world.

¹ The theory of intentionality states that every belief has an object that it is about.

In other words we can either choose to study a given phenomenon (in a phenomenological manner), or we can choose to study how people experience a given phenomenon. Research carried out from this perspective does not see reality as being external, in this manner it is similar to constructivism, but as being constituted as the relation between the individual and the phenomenon. Therefore, the research will be concerned with the relationships that people have with the world around them and from this perspective researchers do not make any assumptions about the nature of reality nor do they claim that their research represents “truth”.

Students will not all experience the same learning and teaching situation in the same way nor will they approach their learning in the same way, even within the same context. Trigwell & Prosser (1996) explained that a student’s perceptions, conceptions and approaches are “not independently constituted but ... are simultaneously present in the student’s awareness” (pg 78), although certain aspects may be in the foreground and others in the background at any point in time depending on the context. Marton (2000, pg 113) discusses awareness, not as a dichotomy, i.e. unaware and conscious, but as “everything that is experienced simultaneously in whatever way it is experienced”. In a complementary and critical review of Andrea diSessa’s monograph (1993), Marton (1993) states that p-prims (as discussed in Chapter 2, section 2.4.2) are, in his view, ways of experiencing or understanding phenomena in the world and that “the development that diSessa sketches from the naïve sense of mechanism to a scientific understanding of physics is not an organisation and restructuring of an unobservable knowledge system but an organisation and restructuring of the way in which the learner is aware of the physical world” (pg 236).

According to Marton & Booth (1997, pg 87) awareness has both a structural and referential (meaning) dimension; the structural involves “discernment of the whole from the context [external horizon]² on the one hand and discernment of the parts and their relationships within the whole [internal horizon]² on the other” and intertwined with the structural aspect is the referential aspect. The external horizon is all that surrounds the experienced phenomenon and the internal horizon are the discerned parts of the experience, the relationship between them and the relationship with the whole.

By experiencing the parts and the whole and the relationship between them it is possible to discern further degrees of meaning. They use an analogy of being able to see a deer in a dark wood to illustrate this. In other words in order to ‘see’ the deer, you must discern its contours and outline from the surrounding trees, but by recognising its contours as contours of a deer, you have already identified it as a deer. In this case the external horizon is coming upon the deer in the woods and the internal horizon is the deer itself and any aspects of the deer which are discerned. In this way Marton & Booth (1997, pg 87) clarify that “structure presupposes meaning, and at the same time meaning presupposes structure. The two aspects, meaning and structure, are dialectically intertwined and occur simultaneously when we experience something”.

Aspects of an experience which are simultaneously discerned may become the objects of focal awareness and are thematised (the theme), while other aspects of the experienced world recede to form the background to the theme, and so are unthematized (the thematic field) (Marton, 2000). Marton makes reference to Gurwitsch (1964) to discuss this

² Brackets added

relationship using gestalt theory, where a gestalt is a collection of physical, biological, psychological or symbolic entities that support each other and determine each other. The aspects of a phenomenon that are brought into focal awareness may be determined by the context of experience. Linder & Marshall (2003 pg 274) provide two physics-related problems to illustrate the distinction between the theme and the thematic field. The first problem being:

A small insect flies directly into the windscreen of a bus traveling down a freeway and is immediately killed as it is splattered onto the windscreen. Compare the relative size of the impact force experienced by the insect and the bus respectively for the period of impact.

They argue that in this case certain aspects may be discerned by an individual, such as the bus, the insect, the relative velocities of the two, Newton's laws, ideas about force and momentum, intuitive thoughts about force and motion, and these make up the thematic field of the situation. The theme would comprise those aspects of the thematic field which were brought into focal awareness and an individual's experience of this problem may differ depending on which critical aspects were brought into focal awareness. Therefore according to Linder & Marshall (pg 275):

Learning is about changing those aspects of the phenomenon that are present in the theme, and the role of teaching, then, would be to focus on the educationally critical aspects of a phenomenon, and in doing so, widen the space of variation for the learner.

Marton & Booth (1997) explain that the way in which an object (physical object or object to be learned) is experienced is a characteristic of which aspects of the object are simultaneously discerned by the individual. Marton & Trigwell (2000, pg 387) state that “there can be no learning without discernment and there can be no discernment without variation”. Therefore it is the variation in the way that aspects of a particular phenomenon or object are discerned that constitutes the learner’s experience of those phenomena (Linder & Marshall, 2003) and this is categorised by the structure of the learner’s awareness.

This theory of variation and awareness (Marton & Booth, 1997; Bowden & Marton, 2004; Marton & Tsui, 2004; Marton & Pong, 2005) has become the cornerstone of the ‘new’ phenomenography (Linder & Marshall, 2003; Pang, 2003) which has shifted recently from methodological considerations to theoretical considerations. Pang (2003) suggests that variation theory has given ontological significance to the ways of experiencing something.

To understand learning contexts and how different individuals act within them it is not sufficient to only examine what is happening, it requires an examination of the individuals’ experiences within those learning and teaching contexts. As my research aims to examine how individuals’ experience, interpret, understand, perceive and conceptualise a phenomenon, I felt a constitutionalist epistemology was the most appropriate from which to ground my research. Trigwell & Prosser (1996) argued that research of a relational nature such as this into learning is entirely consistent with this constitutionalist perspective. It was from this perspective that I formulated the research questions to address the research problem and naturally chose the phenomenographic methodological approach out of which constitutionalism as a theory of knowledge and variation theory as a theory of learning

were borne. In the following section I will provide the reader with a detailed overview of the methodological assumptions of phenomenography and explain how this methodology is the most suitable view point from which to answer my research questions.

3.4 Research Methodology

As a strategy of inquiry or methodology with which to answer the research questions, I chose phenomenography. It has become a popular methodology in education research as it aims to understand the various ways in which different people experience, perceive or understand the same phenomena.

3.4.1 Phenomenography

A wide range of research within the phenomenographic tradition has given account of the different ways in which people experience various phenomena in the world. The adoption of this methodology came about due to the desire to understand why some students were better learners than others. It was Ference Marton who formally introduced the term 'phenomenography' in 1981, which he defined as the empirical study of the variation in the ways in which people experience, perceive, apprehend, understand and conceptualise various phenomena in and aspects of the world around us (Marton, 1981).

Although the relationship between phenomenology and phenomenography has been regarded as unclear (Hasselgren & Beach, 1997), and phenomenography is sometimes seen as a subset of phenomenology, phenomenography did not emerge or derive from phenomenology (Uljens, 1996; Svensson, 1997). Taking a phenomenological approach is to step back from ordinary assumptions regarding things and to describe the phenomena of

experience as they appear rather than attempt to explain why they appear that way, whereas phenomenography aims to find out the qualitatively different ways of experiencing or thinking about some phenomena (Marton, 1994). Furthermore this approach assumes that there are a limited number of qualitatively different ways in which different people can experience a phenomenon. The phenomenographic philosophy is also different in that it does not view the outside world and the individual as separate: reality is not seen as being external but as being constituted as the relationship between the individual and the phenomenon. This non-dualistic feature of phenomenography has its origins in the constitutionalist epistemology from which it was derived as described in the previous section.

Different people will not experience a given phenomenon in the same way, rather, there will be a variety of ways in which people experience or understand that phenomenon. The researcher seeks to identify the multiple conceptions, or meanings, that a particular group of people has for a particular phenomenon or a number of phenomena. Thus, the objects of study in phenomenographic research are the qualitatively different ways in which people experience, or make sense, of different phenomena in the world around them. The outcome of phenomenographic research is therefore a list, or description, of the qualitative variation in the ways the sample participants (e.g. students) experience an object of study, a phenomenon, a concept or an activity (e.g. the study of physics) (Marton, 1986). For instance, in mathematics (Prosser & Trigwell, 1999) phenomenographic research showed the limited variation in the ways students perceive the subject - from those who see it as the “process of using different techniques to solve various problems” to those that see it as “a thinking process”.

Furthermore, Marton (1994) states that the different ways of experiencing different phenomena or concepts are representative of different capabilities for dealing with those phenomena or concepts and that some ways of dealing with phenomena or concepts are more productive than others. Thus, the conceptions, or “ways of experiencing” and their corresponding descriptive categories are not only related, but may also be hierarchically arranged and it is this hierarchy that displays the relation between the categories. The ordered and related set of categories or descriptions is called the “outcome space” of the phenomenon or concept being studied. Marton (2000) states that the outcome space describing the different ways an object (or phenomenon or concept) is understood or experienced constitutes that object, as the object cannot be defined independently of the way in which it is experienced.

As described previously, recent developments have led to a new phenomenography whose aim is to characterise particular ways of experiencing. As Pang (2003, pg 152) states

The new phenomenography studies both the variation among the different ways of experiencing something as seen by the researcher, and the variation among the critical aspects of the phenomenon itself as experienced by the learner.

A way of experiencing a phenomenon or concept can be characterised by the dynamic structure of an individual’s awareness, and that awareness has both a structural and referential aspect. Therefore categories describing the variations in how something is experienced will have both structural and referential components and the categories differ

from each other depending on the critical aspects which are discerned and kept in focal awareness simultaneously. Marton & Booth (1997) state that “a way of experiencing something springs from a combination of aspects of the phenomenon being both discerned and presented in focal awareness simultaneously. An aspect is ... a dimension of variation” (pg 136). The highest hierarchical category will consist of discerned key aspects which are in focal awareness simultaneously whereas low categories may correspond to few or no aspects being discerned, intermediate categories relate to more aspects being discerned and perhaps being used in sequence (Stephanou, 1999).

Marton & Booth (1997) discuss three criteria on which to judge the quality of a set of outcome spaces:

1. Each category should tell something distinct about a certain way of experiencing the phenomena;
2. Categories should have a logical relationship, which is often hierarchical;
3. There should be as few categories as possible, which capture the critical variation in the data.

However, in phenomenographic analysis there is no attempt to ‘fit’ the data into pre-determined categories. Some phenomenographic researchers consider that the categories are constructed from the data and others believe that they are constituted within the data and are therefore discovered (Hasselgren & Beach, 1997; Walsh, 2000). The latter corresponds to my own view and although I began by assuming that a limited number of conceptions and approaches could be found, the data was examined as a whole and during

the analysis I endeavoured to incorporate all aspects of the data. This will be discussed in further detail within the analysis section of this chapter. Bowden (2000) states that one of the characteristics of phenomenographic studies which distinguish them from other approaches (such as alternative conceptions research) is the emphasis on making explicit the relation between the conceptions. Bowden continues in his description of phenomenography by stating (pg 50)

It is important to note that the stance we take is that learning occurs when students move from one level of understanding to another more complete one. Furthermore, the origin of any person's current understanding is likely to include both formal instruction and everyday experience. It is inappropriate to try to separate the aspects of students' understanding that derive from the two forms of experience.

3.4.2 Summary of phenomenography as a methodology

From this methodological approach, it is irrelevant if conceptions are considered “correct” or “incorrect” by current standards; the aim is simply to elucidate the different possible conceptions that people have for a given phenomenon in a given situation. However, it is more than just identifying these conceptions and ‘outcomes spaces’, the analysis involves looking for their underlying meanings and the relationship between them (Entwistle, 1997).

As Åkerlind (2005b, pg 72) states

The aim is to describe variation in experience in a way that is useful and meaningful, providing insight into what would be required for individuals to move from less powerful to more powerful ways of understanding a phenomenon.

For instance one might conduct phenomenographic research to study the qualitatively different ways students' approached their learning and the different ways they perceived their learning environment and in each case an outcome space is developed. Then the researcher can examine the two outcome spaces to find the relationship between how students approach their learning and how they perceive their learning environment. Indeed, this type of relational phenomenographic study has been carried out by a number of researchers (Biggs, 1979; Ramsden, 1992; Marton *et al.*, 1997; Marton & Säljö, 1997;).

3.4.3 History and critiques of phenomenography

Phenomenography has been used and developed as a qualitative research approach in educational research studies for the past 35 years (Marton, 1974; Dahlgren, 1975; Prosser, 1994; Entwistle, 1997) and is theoretically grounded in the interpretivist tradition (Jones, 2004). The first studies were conducted to investigate why some students were better learners than other. These studies aimed to describe the qualitative variation in how university students understood an academic text (Marton, 1974; Dahlgren, 1975; Säljö, 1975; Svensson, 1976). The qualitative differences in the outcome of these studies were

linked to two distinctly different approaches to learning which were later named the deep and surface approach (Marton & Säljö, 1976a; 1976b). These studies opened up the field of phenomenographic research to science educators and researchers who have conducted a variety of research studies concerning the variation in the qualitatively different ways in which students (and lecturers) experience phenomena in the world around them (for example; Johansson *et al.*, 1985 and later Prosser & Millar, 1989 employed phenomenography to describe the nature of conceptions and learning in general; Linder & Erickson, 1989 explored the variations in higher level students' conceptions of sound; Franz *et al.*, 1997 investigated engineering and architectural students' conceptions of learning; Linder *et al.*, 1997 explored self learning development as experienced by tutors; Entwistle *et al.*, 2000 further explored approaches to studying; Johnston, 2001 examined economics and commerce students' approaches to learning and perceptions of their learning environment; Jones & Asensio, 2001 explored students' experiences of assessment; Ingerman & Booth, 2003 used a phenomenographic approach to discover the qualitatively different ways in which students and physicists describe their area of research; Wihlborg 2004 explores the variations in nurses' conceptions of internationalisation; Ingerman *et al.*, 2007 used a phenomenographic approach to discover how students experienced variation while learning via a computer simulation). However, until quite recently few studies gave detailed accounts of the methodological requirements that underlined the phenomenographic approach (Åkerlind, 2005a). Åkerlind believes that this may have aggravated critiques of the approach which are founded on misunderstandings of the approach (for example see: Francis, 1996; Webb, 1997). Ashworth & Lucas (1998) particularly address the fact that the phenomenographic literature had not fully explained the process of revealing the students' experiences. These researchers called for clarification

on issues such as bracketing and the requirement of researchers to set aside personal presumptions and preconceptions in order to elicit students' conceptions. Åkerlind (2005a) addresses these issues generally by highlighting the variations in the ways in which phenomenographic research and analysis has been used and described subsequently in numerous scholarly contributions to the literature.

3.4.4 Rationale and use of phenomenography in this research

For my research, I am interested in examining the variation in a set of students' their approaches to problem solving, the variations in their conceptual awareness and knowledge and in discovering the relationship (if any) between these factors. Although I feel that it is appropriate to answer my research questions using a phenomenographic approach, it is not a "pure" phenomenographic approach. Marton (1986, pg38) suggests that the concepts under study are mostly "phenomena confronted by subjects in everyday life rather than in course material studied in school". Therefore pure phenomenography is not appropriate as the aim of the research is to examine students' understanding in order to enable subsequent use of the outcomes in learning and teaching contexts. Therefore I am using a variation of phenomenography called "developmental phenomenography" (Bowden, 1995). Bowden discusses his groups' use of developmental phenomenography in a number of studies (pg 146):

I describe the kind of research that I do as developmental phenomenography because it is undertaken with the purpose of using the outcomes to help the

subjects of the research, usually students, or others like them to learn. The insights from the research outcomes can help in the planning of learning experiences which will lead students to a more powerful understanding of the phenomenon under study, and of other phenomena like it. The outcomes from these research studies can also be used to develop generalisations about better and worse ways to organise learning experiences in the particular field of study.

As discussed in Chapter 2, Bowden and his research group have carried out a number of investigations into students' experiences and understanding of some key concepts and principles in physics using a developmental phenomenographic approach (Bowden *et al.*, 1992; Dall'Alba *et al.*, 1993; Walsh *et al.*, 1993; Ramsden *et al.*, 1993). Bowden *et al.* (1992) used this research methodology to investigate the understanding of displacement, velocity and frames of reference in a large group of students. In analyses of student interview transcripts, the researchers found that student responses to qualitative and quantitative problems could be categorised according to the variation in the responses. Dall'Alba *et al.* (1993) employed phenomenography to explore the variation in the ways in which acceleration was understood or perceived by the same group of students. The authors, again through analysis of interview transcripts, discovered six categories which described the variation in the way that acceleration was understood. Similarly, Walsh *et al.* (1993) and Ramsden *et al.* (1993) investigated students' perceptions of relative speed and speed, distance and time respectively. Sharma *et al.* (2004) also adopted a phenomenographic methodology to describe the variations in the way in which students understood the concept of gravity. The significance of these studies was that the researchers

were all interested in investigating how the critical aspects of the phenomena as experienced by students varied. In my research my objective was to examine how the critical aspects of the students' awareness varied with respect to conceptualisation of knowledge and approach to problem solving. Therefore, I felt I could employ the phenomenographic methodology and methods used and developed by the researchers described above to undertake my research.

3.5 Data Collection and analysis methods

The dominant method used in the phenomenographic methodology is the open and deep interview, which is carried out in a dialogical manner (Booth, 1997; Åkerlind, 2005a). In my research, the interview was the most important and significant research method but I also used other methods that were chosen to highlight the idiosyncratic nature of learning and place the research in the context in which the data was obtained. Hence, both qualitative and quantitative research methods were used to triangulate the data (Cohen *et al.*, 2000; O'Donoghue & Punch, 2003) in order to draw conclusions. The important feature of this research is that the methods used have produced data, which was analysed in an iterative manner, with the unit of analysis being the different ways of experiencing the phenomena in question. From this unit of analysis the following were determined and this extrapolation is discussed in further detail in the subsequent sections:

- conceptual knowledge of force and motion before formal instruction;
- conceptual knowledge of force and motion after instruction in mechanics;
- conceptual awareness in the context of mechanics;
- approaches to solving quantitative problems;
- conception of acceleration.

The research methods and data analysis processes are described in the following sections.

3.5.1 Force and Motion Conceptual Evaluation

As discussed in Chapter 2 research based diagnostic tools have been widely used to assess conceptual understanding and conceptual learning gains in introductory physics students over the past 18 years. In order to set the conceptual knowledge context for this study and to quantitatively determine if gains in learning (as measured by the diagnostic tool) had been achieved through instruction one such diagnostic tool was employed for this research study. That tool was the Force and Motion Conceptual Evaluation.

Thornton and Sokoloff (1998) developed the Force and Motion Conceptual Evaluation (FMCE) as an instrument “to evaluate student learning in introductory physics courses” (pg 338). A copy of the FMCE is shown in Appendix H. The instrument is a research based multiple-choice assessment that was designed to “probe conceptual understanding of Newtonian mechanics”. The FMCE consists of 47 multiple-choice questions, with all of the questions written in “natural language” and as mentioned previously, many include pictorial representations. The FMCE is structured into clusters of questions associated with a particular situation. Figure 3.1 overleaf is an example of a set of questions from the evaluation and these questions are referred to as “the coin toss” question.

Questions 11-13 refer to a coin which is tossed straight up into the air. After it is released it moves upward, reaches its highest point and falls back down again. Use one of the following choices (A through G) to indicate the force acting on the coin for each of the cases described below. Answer choice J if you think that none is correct. **Ignore any effects of air resistance.**

- A. The force is **down** and constant.
- B. The force is **down** and increasing
- C. The force is **down** and decreasing
- D. The force is zero.
- E. The force is **up** and constant.
- F. The force is **up** and increasing
- G. The force is **up** and decreasing

- _____ 11. The coin is moving upward after it is released.
- _____ 12. The coin is at its highest point.
- _____ 13. The coin is moving downward.

Figure 3.1: Sample set of questions from The Force and Motion Conceptual Evaluation

In general, the inventory is designed to illustrate whether students:

- have a Newtonian view of the world;
- have a non-Newtonian view of the world;
- are developing some Newtonian views.

As stated in Chapter 2, the FMCE is similar to the Force Concept Inventory (FCI), (Hestenes, Wells & Swackhamer, 1992) and the decision to employ the FMCE as a method of investigation in this research was an informed choice. Both tests have been used extensively as evaluation tools (Cummings *et al.*, 1999; Wittmann, 2002; Redish, 2003), but while the FMCE does not cover as much material as the FCI it uses more questions for each concept and approaches the concepts from a number of different contexts. The FMCE

also places more emphasis on students' understanding of graphical representations of velocity, acceleration, and force. Redish (2003) reports on studies carried out by Ron Thornton who found strong correlation between results on the FMCE and on the FCI. Figure 3.2 shows scatter plots of pre- and post-FCI versus FMCE scores (Redish, 2003; pg 104).

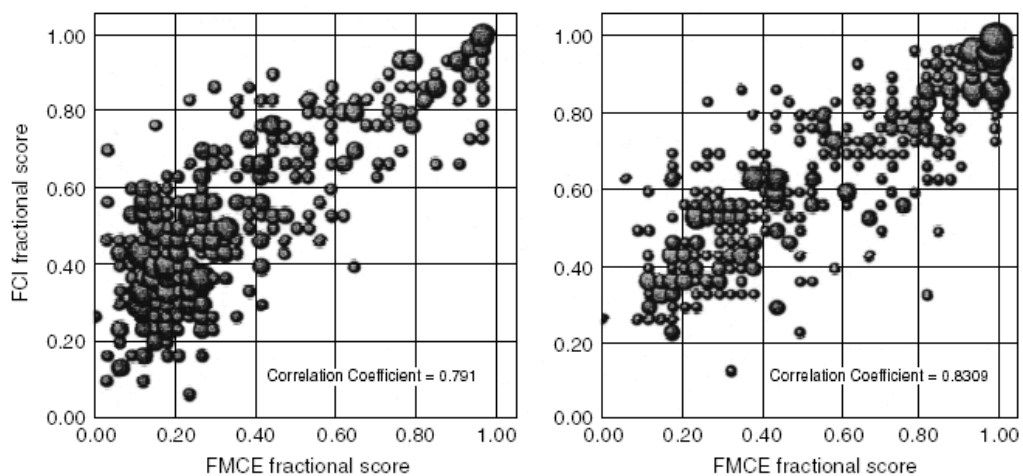


Figure 3.2: Scatter plot of FMCE versus FCI scores pre (left) and post (right). The size of the markers indicates the number of students with those scores (Redish, 2003)

To test the validity of the instrument, Thornton and Sokoloff have evaluated a large number of physics students at many colleges, universities and high schools with the FMCE and compared student responses on multiple-choice versions of the FMCE and versions that consisted of open-ended questions with explanation. They also asked additional questions on examinations to compare with the FMCE results. There was a strong correlation between the student responses to the various styles of questions, particularly the multiple-choice and open-ended with explanation versions of the FMCE questions (>90%). In addition, the pre and post instruction results have proven to be very stable and repeatable

(Thornton & Sokoloff, 1998) when comparing equivalent classes at several different institutions for both traditional and enhanced instruction.

The analysis of the FMCE results was made simple by a Microsoft Excel™ analysis template created by Michael Wittmann (2002). The template allows the user to input students' answers and it then calculates a percentage for each student, as well as the number of questions answered correctly. The template also breaks the questions down into sections, which are 'Velocity', 'Acceleration', 'Force (1,2)', 'Force (3)' and 'Energy'. Force (1,2) and (3) here refer to questions relating to Newton's three laws of motion. It calculates percentage correct for each of these. Both pre- and post- data are inserted into the template and the program will then configure the 'matched data', which means it will give a 'match' if a particular student has completed both of the tests. The template then uses this information to calculate the 'average normalised gain' overall and for each section, as described above. Richard Hake of Indiana University introduced this 'average normalised gain' factor (Hake, 1998).

Average normalised gain = actual gain / maximum possible gain,

or

$$g = (\text{average post-test score} - \text{average pre-test score}) / (100 - \text{average pre-test score})$$

Hake defines the normalised gain on the FCI (or FMCE) test to be the average increase in students' scores divided by the average increase that would have resulted if all students had perfect scores on the post-instruction test. Hake (2002) has carried out extensive research using this method and concludes that "the average normalised gain affords a consistent

analysis of pre-test and post-test data on conceptual understanding over diverse populations in high schools, colleges, and universities” (pg 7). It should be noted here that although the normalised gain has values from 0 – 1 it is represented, for the benefit of the clarity, as a percentage at times during the presentation of the findings in this thesis and this will be highlighted when it occurs.

Further analysis of this data was carried out using SPSS software, all of which is presented in Chapter 4, along with correlations relating to the individual students attributes. These correlations were carried out in an effort to investigate whether other factors influenced how a student learned or understood physics.

3.5.2 Individual Interviews

Although many possible sources of information may reveal a person’s understanding or conception of a particular phenomenon, the method of discovery within phenomenography is usually an individual interview (Åkerlind, 2005a). For my research, I used semi-structured interviews, for which I prepared specific questions but was also prepared to follow any unexpected lines of reasoning. For all interviews I was the sole interviewer; however the interviews were piloted with one staff and two postgraduate members before any students were asked to participate. Two rounds of interviews were carried out; the first set of interviews (Interview set A) consisted solely of quantitative problems, which are described below, and although students’ conceptualisations of concepts such as force and motion were analysed this was not intended as the focus for these interviews. The major

aim of interview set A was to examine the qualitative variation in the way in which these students approached physics problem solving. The second round of interviews (Interview set B), carried out in the following academic year were broader, with the intention to explore students' conceptions of acceleration in relation to force and to further analyse and explore the variations in students' approaches to problem solving. Overall the interviews provided data to answer the following research questions:

- What are the qualitatively different ways in which students in introductory physics courses approach various levels of quantitative problems?
- What are the qualitatively different ways in which introductory students conceptualise mechanics concepts, such as motion and force?
- How does students' conceptual awareness affect the manner in which they approach quantitative problems?
- Can students who do not have a full understanding of certain basic physical concepts correctly answer quantitative problems?

The variations in these students' perceptions of their learning environment were also explored in these interviews. However, this was not considered to be within the scope of the research presented here but the preliminary results of this study are included as Appendix F.

3.5.2.1 Interview set A

The interviews, which were videotaped, consisted a sequence of six physics problems with the first two being typical end-of-chapter linear motion problems. Two of the problems were adapted from context-rich questions developed by the physics education research group at the University of Minnesota. The initial interview protocol was piloted first with a staff member, a volunteer postgraduate student and then a sample student from the cohort of participating students. These pilot interviews were invaluable for improving the interview skills needed to conduct the semi-structured interview, such as putting the interviewee at ease and learning to avoid leading the interviewee. This was only achieved by reviewing the videotapes after the interviews with another member of the group and identifying key areas for improvement. Also minor changes were made to the interview protocol itself and problems used are presented in Appendix C1.

Generally the problems were progressively more complex and therefore if a student did not complete all of the problems it was indicative of his/her problem solving ability. The interview did not have a time limit but ended when the student could not continue. Some of the students completed all six problems while others may only have completed or partially completed two or three problems. Retrospectively, the interviews lasted on average 45 minutes; however no particular time was allotted for the interviews. For instance one student completed all six problems in 55 minutes, whereas for another student who could only attempt two questions the interview lasted 30 minutes. However, for the purpose of this study, this did not pose a difficulty as it was the description of the students' problem solving approaches that were under investigation and not the students' solutions to the

problems. I read each question aloud to the student and the student was then given time to read the problem. The reason the problem was initially read aloud was to overcome any discrepancies in how the students read the problems. The student was asked to state their first ideas on what they thought the problem involved and then asked to describe, qualitatively, how they were going to go about solving the problem. After this, the student was encouraged to 'think aloud' (van Someren *et al.*, 1994) as they solved the problem on paper (which was collected at the end of the interview). An equation sheet was available during the interviews, which contained a list of equations the students encountered during their mechanics module. Once the student had solved, or attempted to solve, the problem they were asked how confident they were in their answer and asked to explain this level of confidence. In this way each interviewee was encouraged to qualitatively analyse their solution. Due to the graded nature of the problems, and with the use of the think aloud protocol, students' approaches and conceptions could be identified.

3.5.2.2 Interview set B

These interviews, which again were videotaped, consisted of three phases; the first I labelled perceptions (not discussed here but referred to with results in Appendix F, as explained previously), the second was conceptual knowledge and the third was problem solving. In the conceptual knowledge phase of the interview, essentially two qualitative questions on force and motion were used as the basis to explore the variations in the ways that the students conceived of acceleration, particularly in relation to force. The focus in this part of the interview was to explore students' understanding by asking follow up questions to the students' answers of the original question. The first qualitative question is

shown below during which the interviewer also enacted the situation by throwing the pen straight up in the air:

Watch as I throw this pen straight up in the air and allow it to fall to the ground. Describe exactly what is happening from the moment the pen leaves my hand until it reaches the ground. You can ignore air resistance.

After the student gave an initial explanation, depending on the details of the explanation, I asked the student to explain further. For example I may have asked the student to describe the pens' velocity or acceleration at any point in the journey and thus explain why that was. The second qualitative question was adapted from the first question set of the FMCE (Thornton & Sokoloff, 1998); the questions posed to the students were as follows:

*Imagine a block moving to the right across a perfectly smooth ice rink with constant speed. What force would keep it moving to the right with constant velocity?
Now imagine that the block is speeding up at a steady rate, with constant acceleration. Is a force required for this to happen? What kind of force?
The block is still moving to the right, what force will slow it down at a steady rate, with constant acceleration?*

Again after each section of the question was posed, depending on the details in the students' explanation, I asked the student to further explain their answer. Each question that was raised in the interviews was done so in order to elicit some aspect of the understanding or perception under investigation and in this way the focus of the interview was maintained throughout (Dall'Alba, 2000). This process will be illustrated further in Chapter 4 while presenting some examples of the interview transcripts.

The third phase of the interview, the problem solving phase, consisted of one quantitative problem which was adapted from problem 3 of interview set A (Appendix C2). However, if a student could not solve or attempt to solve this problem the student was presented with problem 2 from interview set A, which I perceived to be less complex. This stage of the interview was carried out in exactly the same manner as interview set A. I first read the problem aloud to the student and the student was given time to read the problem. I then asked the student their first thoughts and what they thought the problem involved. Following this I asked the student to solve the problem while thinking aloud and again during this phase I asked questions such as ‘why are you doing that?’ or ‘how does that help you?’ As before all questions asked were done so with the aim of drawing out further aspects of the way in which the student was experiencing the problem.

3.5.3 Interview analysis

All of the interviews were then transcribed verbatim from the videotapes. The interviews being videotaped allowed a degree of fullness to the transcriptions which I believe would not have been possible with audio recordings. Any vocal tone shifts were recorded as well as hand and face gestures. Therefore in analysing the data, qualitatively distinct categories emerged that described the variations in the students’ perceptions, conceptions and approaches. I believed that a limited number of categories were possible for each research question and that these categories could be discovered by immersion in the data. A core principle of phenomenographic research is the assumption that categories describing the variation in the ways of experiencing something are related to each other, usually by a

hierarchical relationship (Marton & Booth, 1997). However, John Bowden (2005), among others (e.g. Ashworth & Lucas, 2000), recommends that the analysis of this structural relationship between the categories be postponed until the overall meaning of the categories has been finalised. This is due to the fact that such structural links between the categories requires the researcher to apply their own perspective and at all times during the analysis the researcher's own relationship to the phenomenon or experience must be bracketed. Therefore all analysis should be based solely on the interview transcripts; as Bowden (2005, pg 15) said "if it is not in the transcript, then it is not evidence". But owing to the fact that meaning and structure are "supposed to be co-constituted in phenomenographic analysis" other researchers warn of the dangers of not considering both meaning and structure simultaneously (Åkerlind, 2005a, pg 324). Åkerlind (2005b) states that a strong emphasis on structure is necessary, because one of the epistemological underpinnings of phenomenography is that logical relations exist between different ways of experiencing the same thing. An outcome space is not simply a set of different meanings but should be a logical structure relating the set of meanings. Åkerlind (2005b, pg 72) believes that this is imperative for phenomenographic analysis "because it provides a way of looking at collective human experience of phenomena *holistically*", even though that phenomenon may be experienced by different people in different ways in various contexts. Another reason that Åkerlind (2005b) believes that structure and meaning should be co-constituted from the data is that the resulting outcome space will have more practical application by making the variation in the experience meaningful. Distinguishing the critical aspects in the variations in the ways of experiencing a phenomena and thereby highlighting the structure of these critical aspects allows for a better understanding of how individuals could be helped to move from a lower hierarchical category to a higher hierarchical category.

Therefore Åkerlind (2005c, pg 122) recommends, in searching for dimensions of variation, that “themes of expanding awareness” be identified and discovered within the data:

What I have called ‘themes of expanding awareness’ may be seen as representing structural groupings of dimensions of variation, highlighting the structural relationships between different dimensions. To be accepted as a theme, I required empirical as well as logical evidence of inclusive awareness of each dimension comprising the theme.

In addition to the emphasis on meaning and structure in the outcome space, due to the assumption that when an individual is experiencing something, the structure of their awareness can also be categorised by these two internally related dimensions, structural and referential aspects. During the clarification of the categories the ‘how’ and the ‘what’ students were saying are focused upon. The ‘how’ in this case is ‘how is the explanation given?’ and the ‘what’ is ‘what is focused on?’ (Trigwell, 2000).

Marton (1986) states that phenomenography provides categories that are qualitative, experiential, relational and content-oriented. Svensson (1997, pg 171) further outlines the methodological assumptions involved in the analysis of phenomenographic research by arguing that the categories of description must be based on “exploration of delimitations and holistic meanings of objects as conceptualised” and also that categories are based on “differentiation, abstraction, reduction and comparison of meaning”. The categories are not constituted from every detail in the interview transcripts rather they represent a small

number of holistic meanings with a focus on key aspects of the experience which serve to link and separate the different categories of description. The process of analysis calls for the researcher to differentiate between critical variation and non-critical variation, with critical variation being described as “that which distinguishes one meaning or way of experiencing a phenomenon as qualitatively different from another” (Åkerlind *et al.*, 2005, pg 82), whereas non-critical variation is described as occurring within a way of experiencing and therefore does not distinguish between ways of experiencing.

However, throughout the initial stage of examining the transcripts, I endeavoured to keep a high degree of openness to any possible meanings. For both interview set A and B each transcript was considered as a whole. Although interview set B consisted of three phases, I felt that it was necessary to examine all aspects of each individual’s experience of physics. For example a student may have discussed acceleration in a certain way during the conceptual knowledge phase of the interview and then used or discussed acceleration quantitatively in a different manner; this highlighted further variations in the ways that acceleration was understood. I also felt it was important to examine the transcripts as a group and not as individual samples as phenomenographic research aims to explore the range of meanings (the pool of meaning) within a group and the categories which constitute the outcome space represent the range of ways of experiencing a phenomenon. As Åkerlind (2005a, pg 330 & 331) states:

The aim is not to capture any particular individual's understanding, but to capture the range of understandings within a particular group. The interpretation is, thus, based on the interviews (more precisely, the interview

transcripts) as a holistic group, not as a series of individual interviews.

This means that the interpretation or categorisation of an individual interview cannot be fully understood without a sense of the group of interviews as a whole.

During the first iteration of analysis I looked for both similarities and differences among transcripts, selecting significant statements and comparing these statements in order to find cases of variation or agreement and thus grouping them accordingly. Marton & Booth (1997) describe phenomenographic categories of description as being constituted by considering variation, discernment and simultaneity and this is what I endeavoured to do at all times. I read the interview transcripts many times, each time with a particular aspect of the interview theme in focus and this was carried out using an essentially two-stage analysis. The first stage involved identifying and describing the overall meaning of approaches or conceptions by highlighting and separating the section of the transcripts according to the themes which were apparent, thus representing the ‘how’ aspect. The second stage, which represented the ‘what’ or structural aspect, involved identifying what was focused upon within each overall meaning and searching each preliminary category and the transcripts as a whole for themes of expanding awareness.

Through this process initial hierarchical categories were constituted that described the variations in the ways that these students’ conceptualised, approached and perceived these aspects of physics. For Interview set A, once this initial categorisation was complete, a sample of the interview transcripts was given to two other researchers (BB and RH) from the Physics Education Research Group who then individually carried out a similar analysis

of those transcripts. I then met with the researchers to discuss their categories and their interpretation of the answers and through this discussion the categories were then revised until the researchers reached a consensus about the final set of categories. Bowden (2000; 2005) strongly advocates a group process in phenomenographic analysis, whereas Åkerlind (2005a; 2005b) suggests that it is more than possible to carry out reliable and valid phenomenographic research as a sole researcher. I was the primary researcher in this study and therefore was responsible for carrying out the majority of the analysis; however for the first set of analyses I felt that the input of other group members would add validity and reliability to the results. For interview set B I was the sole analyser, although I did get feedback on the categories of description which were constituted from interview set B.

With the initial categories in mind, I re-examined the interview transcripts to determine whether the categories were sufficiently descriptive and indicative of the data. If there were cases that I felt could not be described by a category, the categories and the interview transcripts were re-examined and in some cases the descriptions were altered to ensure every aspect of the experience under investigation was described. At this stage extracts from the transcripts were sought to support the descriptions of the categories, which I felt gave substance to the categories. This iterative data analysis procedure is consistent with a phenomenographic approach (Marton & Pong, 2005; Åkerlind, 2005a), as Marton (1986, p. 43) states “definition for categories are tested against the data, adjusted, retested, and adjusted again”. Also as Marton and Booth (1997, pg 134) eloquently state “the data shimmers in the intense light of our analysis”. For each research question an outcome space was developed, that included the minimum number of categories, which explained all the variations in the data. Once I had defined the stable outcome spaces I then analysed how

the structure of the individual categories logically related to each other and how the outcomes spaces related to each other. This entire process is described in more detail in Chapter 5 while outlining how each outcome space was constituted.

3.6 Research Participants

As of September 2007, the School of Physics in DIT had three 4-year programmes in which students entered specifically to study physics, which were all level 8 (NQAI) programmes and first year physics was delivered through problem based learning (Bowe, 2006, 2005; Bowe and Cowan, 2004). There was also a 3-year, level 7 programme, in which the students enter first year to study 'science', and it is only in second year that students choose either physics, chemistry or biology. As of September 2006 the first year physics course of this programme was also delivered through problem based learning and incorporated a form of Peer Instruction (Mazur, 1997). A short description of these problem based learning courses was given in Chapter 1. The remainder of the 12 programmes from which the research participants came from are 'service modules' in physics. This means that physics is only one module of the whole programme and the programmes varied from level 7 (e.g. food science) to level 8 (e.g. engineering) and the mechanics sections of these modules were all delivered in a traditional lecture based format.

Over a period of three consecutive years all students entering the programmes described above were asked to complete the pre- and post- FMCE, with the exception of the five service courses in the final year (the reason for this will be explained in Chapter 4). Many of the students entering first year in DIT have not studied physics for the Leaving Certificate and the entry points for the research participants, ranges from 160 to 530. The demographics of the students will be explored in more detail in Chapter 4, where all of the data from this part of the study is presented. Another cohort of students also participated in

the study in a minor role, a group of students entering another Irish IT (Institute of Technology) were asked to complete the FMCE prior to any formal instruction in mechanics. These results can be seen in Chapter 4 and have simply been used as a comparison to the Dublin Institute of Technology students.

3.6.1 Interview participants

The participants for the interviews were chosen based on the results of the Force and Motion Conceptual Evaluation (FMCE), in order to obtain a cohort with a cross-section of abilities. The students' results were grouped into low, medium and high and an equal number of students were randomly chosen from each group. The chosen students were contacted and asked to volunteer for the interviews and only three declined which was encouraging as no incentive was offered. The interviews were carried out over a two-week period following six weeks of formal instruction in mechanics. In addition to the student interviews, one lecturer interview was conducted with an academic member of the School of Physics. The procedure for this interview followed that of the others with the lecturer asked to think aloud during the interview and it was videotaped. This lecturer interview and its purpose will be discussed in some detail in Chapter 5.

Forty two participants were selected for interview from five of the programmes in DIT; three of the programmes were the 4-year (level 8) honours degree physics programmes delivered through problem based learning and these programmes were Physics Technology, Physics with Medical Physics and Bioengineering and Science with Nanotechnology but

they had a common first year programme. Another was the 3-year (level 7) ordinary degree general science programme and the last two were 4-year (level 8) honours degree programmes in Forensic and Environmental Analysis and Clinical Measurement respectively. The latter two programmes were delivered in a predominantly traditional manner and although a different lecturer delivered each the syllabi for mechanics were identical. The participants were all in their first year of study and the sample comprised of 22 male and 20 female students, ranging in age from 18 to 24, and the participants in this part of the study had all completed the Irish Leaving Certificate.

3.7 Ethical Considerations

As the primary focus of this phenomenographic study was introductory physics students' approaches to and conceptions of certain aspects of physics, and the relationship between them, my conceptions of those phenomena were not a focus of this research study. Marton (1994, pg 4427) states "as phenomenography is empirical research, the researcher (interviewer) is not studying his or her own awareness and reflection, but that of the subjects". Therefore, I attempted, as much as possible, to act as a 'neutral foil' for the conceptions and approaches expressed by the participants.

An ethics statement and a subsequent letter of consent were presented to all the participants in this research (ethics statement and letter of consent can be found in Appendix G). Evans and Jakupc's (1996) view informed consent as the key issue in research with humans, particularly in an educational sense. Therefore the ethics statement briefly outlines the nature, scope and purpose of the project and also indicates that all data gathered will be treated confidentially and students are under no obligation to participate. It also includes a statement that each participant is free to withdraw consent and discontinue participation in the research at any time without prejudice. All participants are offered the opportunity to remain anonymous when the outcomes of the research are published.

3.8 Chapter Summary

This chapter has situated this study in the context of interpretivism due to its focus on students' experience, approach and understanding. The theoretical assumptions were discussed and justified and the research was firmly placed within the phenomenographic tradition. The methods associated with a phenomenographic approach as the methodology were adopted to carry out this research and answer the research questions. Through analysis of the data obtained from these methods and by comparing the resulting categories and outcome spaces and seeking relationships, it was possible to answer the following research questions:

- What conceptual physics knowledge do students have when beginning higher education?
- Do students begin to develop sound conceptual knowledge after formal instruction?
- What are the qualitatively different ways in which introductory physics students approach problem solving?
- What are the variations in these introductory students' conceptual awareness?
- What are the qualitatively different ways in which introductory physics students perceive the concept of acceleration?
- What is the relationship between conceptual awareness and approach to problem solving?
- Can students who have not developed sound conceptual awareness solve quantitative problems of differing context?

- Can all students with a coherent conceptual model transfer their understanding to complex, context rich problems?

The following four chapters contain the findings from this research study and within these chapters the findings are discussed and the research questions outlined above are answered.

CHAPTER 4

QUANTITATIVE EVALUATION OF CONCEPTUAL KNOWLEDGE

4.1 Introduction

The previous chapter described the methodology and methods used in this study to obtain the data needed to begin answering the research questions. This chapter aims to set the scene for the chapters which follow by introducing the reader to the students who have participated in this study. It is the only chapter which includes quantitative data to describe students' knowledge and is therefore a point of departure within the thesis, however it should be viewed as a context setter for the chapters which follow. Here the findings from the analysis of the data are presented and are then discussed in detail in relation to this study and relevant studies from the literature.

As discussed earlier the aim of using the FMCE was to investigate the students' initial conceptual knowledge state and therefore this chapter presents the FMCE data obtained both pre-instruction and post-instruction. The data from the pre-instruction evaluations is first presented separately, and then the matched data is presented, i.e. the gain in conceptual knowledge as shown from the FMCE results. A summary of the findings is presented at the end of each section and the chapter concludes with an in depth discussion of the findings

from the FMCE. The findings from the phenomenographic interviews will then be presented and discussed in the following chapters.

4.2 Findings from the Force and Motion Conceptual Evaluation

As discussed in Chapter 3 the FMCE was administered to all students from 12 programmes in DIT over three consecutive years – with the exception of five programmes in the 3rd year. The reason for this exception was that data obtained from the service modules had remained consistent over the previous two years and although I administered the evaluation to three of these programmes in the final year, I did not feel it was necessary to evaluate all eight programmes for the purposes of this research. It was clear from the data that the results for these programmes remained consistent from year to year, as will be illustrated later in this chapter.

The pre-FMCE was administered to students within the first week of semester 1, before any formal instruction in mechanics had taken place. For comparison students from another Irish Institute of Technology were also asked to complete the evaluation before they had encountered any instruction in physics. The post-FMCE was also administered after the mechanics module of each programme in DIT had been completed.

4.2.1 The initial knowledge state of introductory physics students

In total over the three year period of the research more than 600 introductory physics students from DIT completed the FMCE prior to receiving formal instruction in mechanics. Of these 56 % were male and 44 % were female. Table 4.1 shows the pre-FMCE scores for

all students and as can be seen there is no significant difference between the female and male scores; however the gender aspect was not a focus of this research and the results are only presented here for interest's sake. The uncertainty shown is the standard deviation of the mean, σ / \sqrt{N} , also called the standard error, where σ is the standard deviation and N is the sample number.

Table 4.1: Mean Pre-FMCE results

	Number of students	Mean FMCE score %
Total	622	11.60 ± 0.30
Male	347	12.13 ± 0.45
Female	275	10.93 ± 0.35

Table 4.2 shows the distribution of results for the pre-test with regards to the students' previous physics education experience. The students in the 'other' category are students who have studied physics since leaving second level education, which may have been in the form of a post Leaving Certificate course or another third level programme. The results show that honours students and students who have studied physics elsewhere obtain only a slightly higher score than ordinary level students or those who fail.

The majority of the research participants did not begin college with the intention of obtaining a qualification in physics, as it was only the students from the level 8 physics programmes who specifically choose physics before they began college. Table 4.3 is a breakdown of students' pre-FMCE score based on whether or not students entered with the intention to study physics. The third and final set of students in this Table are the level 7

students who enter college to study a general science degree and it is only in second year that they may choose to study physics specifically. As can be seen students choosing physics seem to have slightly more conceptual knowledge (as measured by the FMCE) before any formal instruction in mechanics has taken place in higher education.

Table 4.2: Breakdown of previous physics experience and pre-FMCE score

Previous physics level	Total number	Mean Pre-FMCE %
Honours	101	15.49 ± 1.26
Ordinary	61	11.09 ± 0.69
Fail	16	11.76 ± 1.79
Other	9	16.17 ± 3.43
No physics	435	10.67 ± 0.26

Table 4.3: Mean pre-FMCE score based on students degree choice

Degree choice	Total number	Mean Pre-FMCE %
Physics	54	17.40 ± 1.93
Non-physics	463	10.88 ± 0.29
General science	107	11.93 ± 0.98

As discussed in Chapter 3, the FMCE specifically aims to highlight whether students do or are beginning to, view force and motion in a Newtonian manner as certain sets of questions are designed to examine specific concepts. Michael Wittmann's Excel template (Wittmann, 2008) breaks down the FMCE results with regards to velocity, acceleration, forces (based on Newton's 1st, 2nd and 3rd law) and energy. Figure 4.1 is a graph of the breakdown for all the DIT students who completed the FMCE before any instruction in mechanics. 'Overall' indicates the total mean score, then the mean percentage score for each concept is presented. As can be seen from the graph the major difficulties occur with acceleration and forces. Figure 4.2 is the same graph constructed using the results from the other Irish IT students (52 students) who participated and as can be seen there is little or no difference between the initial knowledge states of the two cohorts of students.

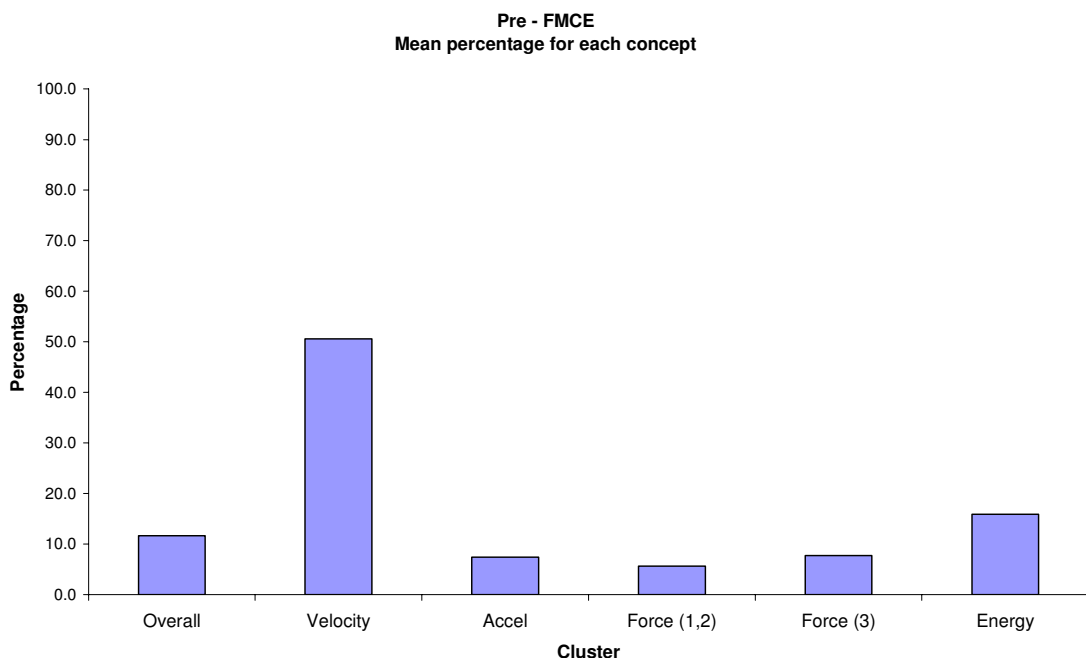


Figure 4.1: Breakdown of pre-FMCE scores for all DIT student participants

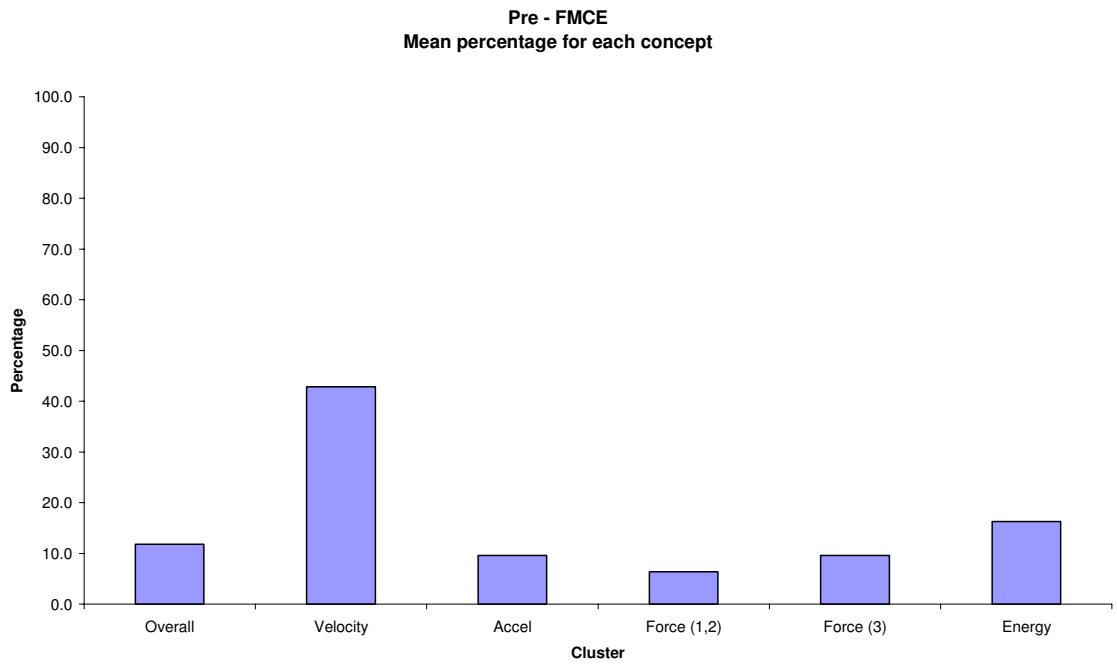


Figure 4.2: Breakdown of pre-FMCE scores for all Sligo IT student participants

4.2.2 Does conceptual knowledge improve after formal instruction?

After the pre-FMCE had been administered to all participating first year students each year, these students then undertook a course of formal instruction in mechanics. Once their mechanics modules were complete, I asked the same students to do the FMCE post-test. As discussed in Chapter 3 the post-test was given to considerably fewer students than the pre-test due mainly to absence and thus in total 378 students completed both the pre- and post-tests. These 378 students make up the ‘matched’ data for this part of the research, where ‘matched’ refers to data obtained from students who carried out both the pre- and post-FMCE. The post-test results are not presented in detail here, as instead I will present the normalised gain (Hake, 1998) which takes account of the differences in the initial starting knowledge of students – as discussed in Chapter 3. Again in all cases the uncertainty is the standard error.

Table 4.4 shows the mean normalised gain for the matched data and the mean normalised gain for all male and female students participating from DIT (matched). For the purposes of clarity the normalised gain is shown to four significant figures.

Table 4.4: Mean normalised gain for students who completed both pre- and post-tests

Students	Total number	Mean normalised gain
All students	378	0.0437 ± 0.0077
Male	218	0.0579 ± 0.0117
Female	160	0.0244 ± 0.0083

Table 4.5 below illustrates the relationship between previous physics experience and the conceptual knowledge gained through instruction as measured by the FMCE. The normalised gain is shown for students who studied Leaving Certificate physics at honours and pass level and for those students who had not studied physics prior to entering DIT.

Table 4.5: Breakdown of previous physics level and mean normalised gain

Previous physics level	Total number	Mean normalised gain
Honours	71	0.1202 ± 0.0286
Ordinary	31	0.0449 ± 0.0230
Fail	11	0.0271 ± 0.0407
Other	7	0.1210 ± 0.0837
No physics	258	0.0211 ± 0.0065

As can be seen from Table 4.4 there is a small difference in mean normalised gain between the male and female students, however at those extremely low gain values statistical significance cannot be attributed. Table 4.5 demonstrates that students with previous physics experience do achieve correspondingly higher gains; however the gains are also very low and the standard error is relatively large. Statistically significant differences only begin to be observed when the students' chosen degree is taken into account as can be seen from Table 4.6 which illustrates the relationship between mean normalised gain and the groups of students' choice of degree.

Table 4.6: Mean normalised gain based on students degree choice

Degree choice	Total number	Mean normalised gain
Physics	49	0.2264 ± 0.0422
Non-physics	252	0.0048 ± 0.0048

Table 4.6 clearly shows that students in the physics programmes have higher gains and this could be due to an inherent interest in the subject. This hypothesis is supported when normalised gain in the FMCE is correlated with previous physics experience and degree choice as illustrated in Table 4.7. Although those students choosing a degree in physics who have studied physics previously achieve higher gains than their counterparts who have not studied physics in school, these students still achieve higher gains than students choosing a degree in an area other than physics.

Table 4.7: Mean normalised gain based on students degree choice and previous physics experience

Degree choice	Previous physics (Leaving Certificate)	Mean normalised gain
Physics	Yes	0.2498 ± 0.0563
	No	0.1197 ± 0.0379
Non-physics	Yes	0.0216 ± 0.0108
	No	0.0052 ± 0.0536

Another factor that could be impacting on the mean normalised gain achieved by these groups of students is the method of delivery of the course material and this will be

illustrated below. Table 4.8 below repeats the findings from Table 4.6 but now includes the normalised gain for the students from the general science degree.

Table 4.8: Mean normalised gain based on students' degree choice

Degree choice	Total number	Mean normalised gain
Physics	49	0.2264 ± 0.0422
Non-physics	252	0.0048 ± 0.0048
General science	79	0.0597 ± 0.0125

Table 4.8 still shows that those students in their first year of study who have chosen physics as their primary degree show significantly higher gains than the other two groups of students. This is true over the three years in which this study has been carried out, as is shown in Table 4.9.

Table 4.9: Mean normalised gain based on students degree choice over 3 years of this study

Degree choice	Year of this study	Total number	Mean normalised gain
Physics	1	11	0.2060 ± 0.0958
	2	19	0.2189 ± 0.0567
	3	18	0.2021 ± 0.0783
Non-physics	1	146	0.0030 ± 0.0061
	2	75	0.0073 ± 0.0088
	3	30	0.0274 ± 0.0152
General science	1	25	0.0096 ± 0.0190
	2	29	0.0912 ± 0.0202
	3	25	0.0762 ± 0.0218

However, an interesting finding highlighted in Table 4.9 is that in years 2 and 3 of this study, students from the general science degree exhibit relatively higher gains than in year 1. This is interesting because it was in year 2 of the study (2006) that the delivery of the physics module of this programme changed from traditionally lecture based to problem based learning.

A further way to look at these results is to examine these groups of students' conceptual knowledge of the particular concepts which are measured by the FMCE. Figure 4.3 is a histogram illustrating the overall mean pre- and post- FMCE percentage scores and percentage gain for the level 8 (physics programmes) students from year 1 of the study. The corresponding histograms for years 2 and 3 can be seen in Appendix D1.

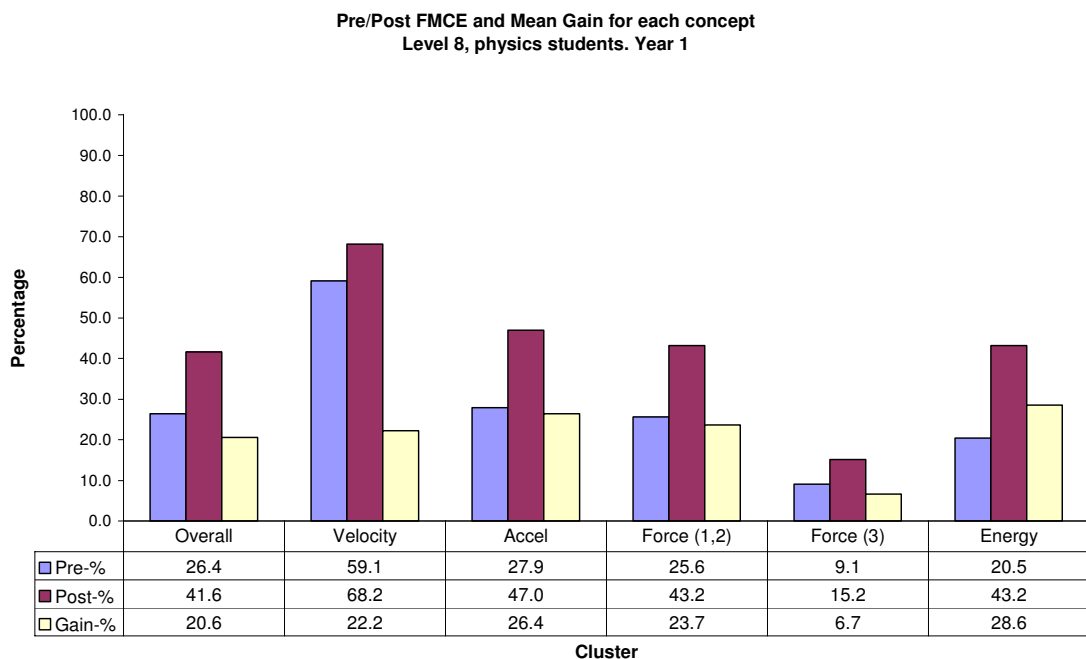


Figure 4.3: Bar Chart of FMCE scores for level 8 students, year 1 of the study. (Normalised gain is shown here as a percentage for reader clarity)

Figure 4.4 is an illustration of the pre- and post-FMCE scores (percentage) and mean normalised gain (percentage) from year 1 of the study for the students who entered college to study a primary degree other than physics. Illustrations of the results for these students in years 2 and 3 of the study can be found in Appendix D2. Although these are students from 8 different programmes, each with a different lecturer, during the course of the study the data from each of these classes have been so similar that I felt they should be grouped as a single cohort of students.

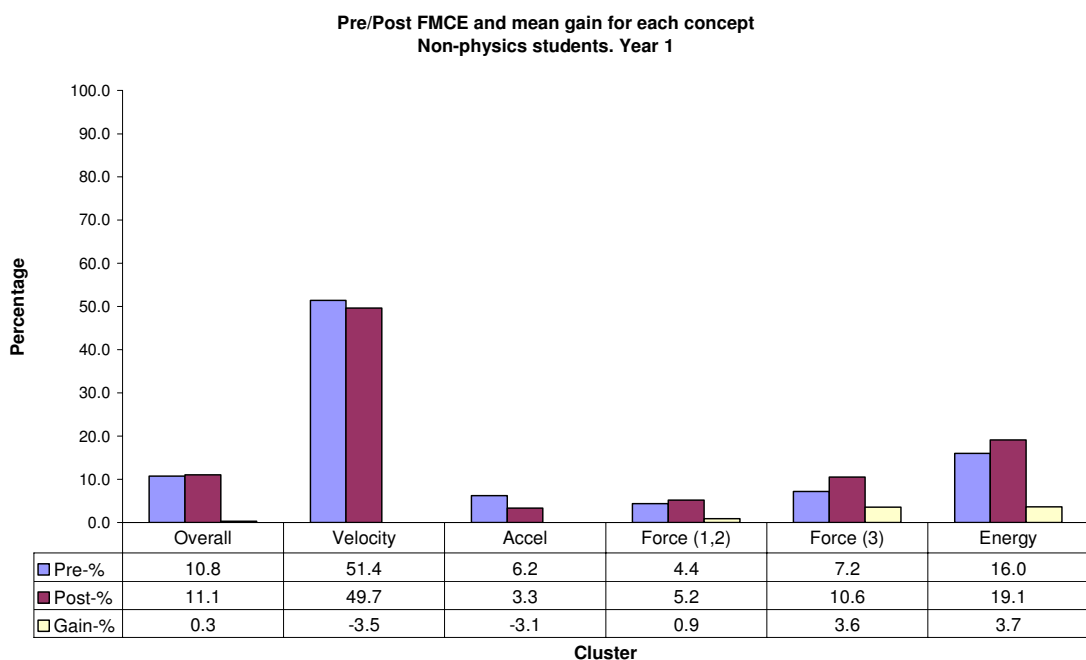


Figure 4.4: Bar Chart of FMCE scores for non-physics students, year 1 of the study

The final set of histograms shown below (Figures 4.5a, b) are the FMCE results for the level 7 general science students for the first two years of the study respectively. Figure 4.5a

illustrates that this cohort of students' gains are comparable with the non-physics students' for each of the three years of the study. In years 2 (Figure 4.5b) and 3 (Figure D3 in Appendix D3) however the students are showing signs of beginning to think in a Newtonian manner. Although the gains are still very low, it does appear that the method of delivery of the course material has had an effect on the conceptual knowledge gained by students from this programme. All other variables remained the same over the three years, i.e. the same lecturers, approximately the same male to female ratio, roughly the same socioeconomic and academic backgrounds and the same average CAO points achieved in the Leaving Certificate.

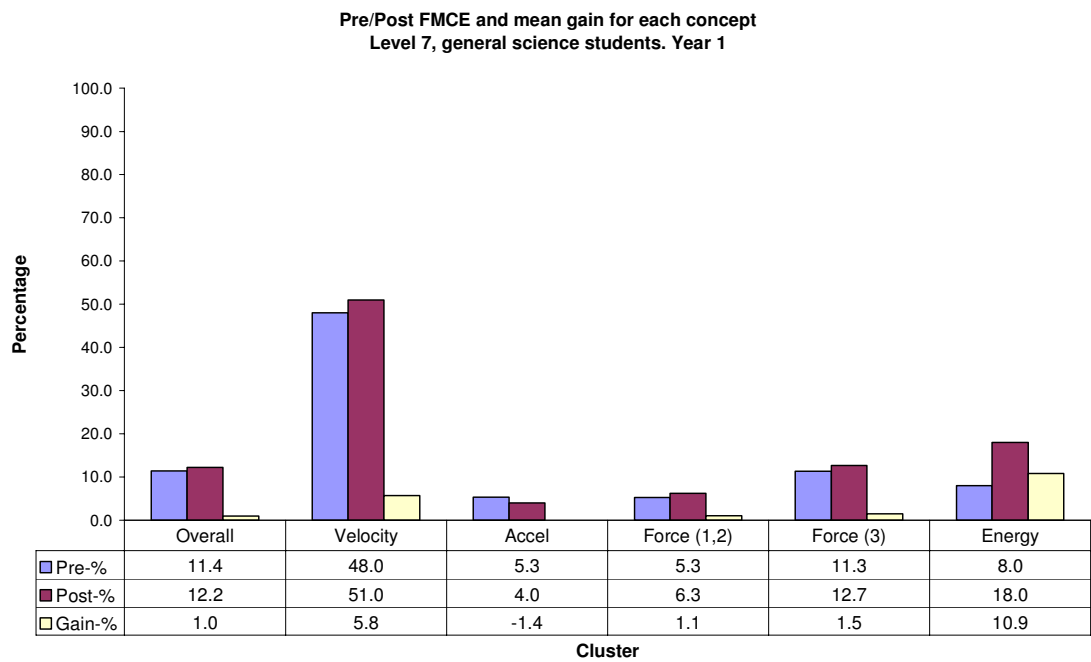


Figure 4.5a: Bar Chart of FMCE scores for general science students, year 1 of the study

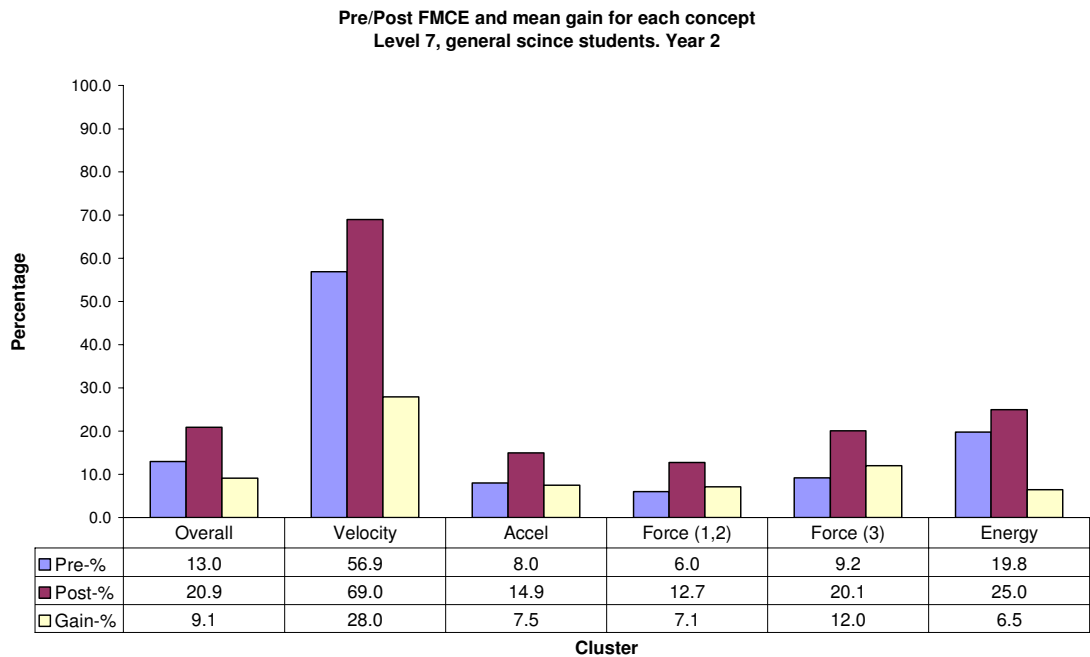


Figure 4.5b: Bar Chart of FMCE scores for general science students, year 2 of the study

4.2.3 Summary of Force and Motion Conceptual Evaluation data

The analysis of the Force and Motion Conceptual Evaluation provides a quantitative description of the initial knowledge state of the students who participated in this study. It also provides an insight into the conceptual knowledge gained after formal instruction in the area of mechanics. These findings provide the context in which the subsequent phenomenographic findings are discussed throughout the remainder of this thesis.

4.3 Discussion of the findings from the Force and Motion

Conceptual Evaluation

4.3.1 Initial knowledge state of introductory students

The Force and Motion Conceptual Evaluation measures conceptual understanding, or as Hoellwarth *et al.* (2005) comments “the questions require conceptual knowledge in order to answer them correctly” (pg 460). According to Thornton and Sokoloff (1998) when the FMCE is used pre and post instruction it can be used to evaluate student learning in mechanics. The pre-instruction FMCE findings from this study imply that the cohorts of students, over three consecutive years, do not view the physical world in a Newtonian manner and the exceptionally low mean score suggests that they had not begun to develop a Newtonian view. This is consistent with extensive previous research not only using the FMCE but also with the Force Concept Inventory (Hestenes *et al.*, 1992; Hake, 1998). Hestenes and Halloun (1995) suggest that a score of 60% on the FCI is the “entry threshold” to Newtonian physics and that students who reach that threshold have only begun to coherently use Newtonian concepts in their reasoning. However, the authors of the FMCE do not suggest such a threshold in the presentation of their research.

The majority of students involved in this study had no previous physics experience, so it makes sense that the results show that these students choose incorrect common sense answers around 90% of the time. However, as can be seen in Table 4.2, there is no significant difference between their scores and the scores achieved by students who had

studied physics in school, including those students who had studied higher-level physics (the four or five percent difference in score between higher-level physics students and those who had not previously studied physics represents on average one more correct answer). Examination of the pre test results for students choosing specifically to obtain a degree in physics shows that the average score is slightly higher ($\approx 5\%$), but when the smaller number of students along with the relatively large standard error are taken into account there is no significant difference between these first year students. Likewise students from the second Irish institute who participated in the study achieved very similar pre-instruction average scores on the FMCE. This suggests that the students are not developing an understanding of the conceptual nature of physics in school and this is consistent with similar research carried out across the globe (Halloun & Hestenes, 1985a; Halloun & Hestenes, 1985b).

4.3.2 Knowledge state after formal instruction

As previously discussed the Force and Motion Conceptual Evaluation is designed to be administered both prior to and following formal instruction in mechanics and for the participating students within the Dublin Institute of Technology this was the case.

It is clear from the results of the post-test that the majority of students experience little or no gain in conceptual knowledge after a formal module of instruction in mechanics as evaluated by the FMCE. The overall mean normalised gain of 0.04 is extremely low and this gain is even lower for those students who enter higher education with a view to

studying something other than physics as their major subject; in fact it is effectively zero. As described in Chapter 1 these ‘service’ modules are all taught in a traditional manner, however the students’ perceptions of the module or their experience of learning physics has not been addressed here and this may provide some insight as to why these students appear to have completed the mechanics module without any understanding of the concepts involved. When the results for all cohorts are considered together students appear to have some understanding of velocity before instruction, however there is no evidence of an overall significant gain in understanding after instruction. This implies that students have some understanding of the concept but are unable to transfer that understanding in another context or develop that understanding through further instruction, and that this issue has not been addressed by conventional instruction. As for the other individual conceptions evaluated by the FMCE, i.e. acceleration, forces 1, 2 & 3 and energy, the average pre-instruction score is almost identical to the average post-instruction score.

Does this evidence validate the claim that students hold stable, robust misconceptions? (Halloun & Hestenes, 1985a; 1985b; McDermott, 1991; Hake 1998; Knight 2002) Or is it evidence that students are using discrete phenomenological primitives in incorrect contexts? (diSessa, 1993) Or do these results simply point to the knowledge state of this set of students; illustrating how these students are aware of the physical world? (Marton, 1993) Through instruction, the students have not yet learned to perceive these concepts in a more powerful way, therefore their awareness of the concepts and the conceptual context has not been reorganised or restructured. The FMCE alone cannot answer these questions, therefore interviews were used to examine the conceptual knowledge state of a sample of these

students and the results of the interviews will be discussed in this context in Chapters 6 and 7.

Instead of looking at the entire population, if the results for mean normalised gains are examined in terms of previous physics experience the story is a little different. Those students who had studied physics at honours (higher) level in school and those who had previously studied physics as part of another programme do show a mean normalised gain which is relatively larger than their counterparts (refer to Table 4.5). This suggests that students who have an apparent interest or indeed a vested interest in the subject may achieve a slightly higher level of understanding after a formal module in mechanics at third level. Another factor that must be taken into consideration here is that only a proportion (38%) of the students who had studied honours physics in school were enrolled in one of the honours degree physics courses. However, Table 4.7 shows that those students in non-physics programmes who have studied physics in school achieve lower gains than all of the students in the physics programmes. When the gains for the students in these three programmes are examined over the three consecutive years, it becomes obvious that the level 8 physics students are achieving higher gains than students enrolled in any of the other programmes. As mentioned in Chapter 3, the pedagogical method of delivery for the three physics programmes is problem based learning. The findings suggest that these students are developing conceptual knowledge much more than their counterparts in other programmes within DIT. There are a number of differences between the physics major students and the non-physics major students that could be responsible for this difference:

- Students begin with the intention of studying physics, therefore they could be more enthusiastic about their learning and approach the subject in a different manner;
- Physics is delivered through problem based learning;
- Assessment is 'open book'; therefore it does not focus on memorisation of definitions and formulas.

I will return to this discussion at the end of this section, however I believe it is first important to refer to the general science students. Within the first year of this study they, as a group, achieved a mean normalised gain of 0.01 which is comparable with the gains achieved by the non-physics majors. However, within the second and third years of the study the gains achieved were considerably higher, without a significant increase in standard error (0.09 in 2006 and 0.08 in 2007). Again, although the mean normalised gains shown here are low, it would appear that some factor influenced these students' conceptual knowledge in a positive way. The cohorts in years 2 and 3 were similar to that in year 1; in gender, in previous physics experience, in entry points and so on. The only significant difference was that in year 1 of the study the physics module was delivered in a traditional lecture based manner and in years 2 and 3 was predominantly delivered through problem based learning. The students who enrol in the general science programme, which is a three year ordinary degree, are historically and generally not enthusiastic about studying physics as the majority enrol with the intention of obtaining a degree in biology and a large number (64%) have not studied physics previously. Assessment of the physics module within this programme is carried out in traditional closed book examinations.

The results point to the conclusion that the delivery method alone influenced the students' gain in conceptual knowledge as measured by the FMCE. The level 8 students who learned physics through pbl achieved considerably higher gains than their counterparts. Furthermore when the delivery method for the level 7 science students was changed from traditional to problem based learning these students also achieved higher gainer than previously attained. However, this raises yet more questions: How did the delivery of the physics module through problem based learning facilitate these students' learning? Did it encourage the students to perceive the physical world in a more powerful way? Or could it have changed their perceptions of their learning environment, thus encouraging self-directed learning? Although these questions will not be answered within this thesis as they are beyond the scope of the study presented here, I intend to explore these questions and their answers in future work in the area.

4.4 Chapter Summary

The Force and Motion Conceptual Evaluation was employed in this research as a means to investigate, quantitatively, the initial and post-instruction conceptual knowledge state of the groups of students taking part in the study. The results strongly suggest that those students who experienced physics through problem based learning are beginning to develop more conceptual knowledge than their counterparts who experienced traditional physics instruction. The results discussed here are similar to results obtained from studies carried out all over the world, employing both the FMCE and the FCI (Force Concept Inventory) to explore gains in conceptual understanding (For example see, Hestenes *et al.*, 1992; Hake, 1998; Thornton & Sokoloff; 1998) and still more studies simply showing that students do not overcome conceptual difficulties having completed formal courses of instruction in mechanics (For example see, Trowbridge & McDermott, 1980; 1981; Peters, 1982; Gunstone, 1987; Kim & Pak, 2002; Shaffer & McDermott, 2005;). Within many of these studies students only begin to achieve development of conceptual knowledge through the implementation of some form of active engagement within the learning environment. For example Thornton and Sokoloff (1998) reported gains on the FMCE through the use of *Interactive Lecture Demonstrations*; McDermott and the Physics Education Group in the University of Washington (1996; 2002) employed pedagogical tools such *Tutorials in Introductory Physics* and *Physics by Inquiry* to produce gains in conceptual knowledge.

For the most part, the FMCE has been used in this study as a way in which to set the context of the research. However, the results have led to further questions which will be

addressed throughout the following chapters in an attempt to resolve the issues raised within this discussion.

CHAPTER 5

VARIATIONS IN APPROACHES TO PROBLEM SOLVING

5.1 Introduction

The preceding chapter discussed the quantitative results from the Force and Motion Conceptual Evaluation and answered the first research question:

- What is the conceptual physics knowledge state of students entering higher education in Ireland?

This chapter is the first of three which presents and discusses the findings from the analysis of the phenomenographic interviews which were conducted for this study in the attempt to answer the following research questions:

- What are the variations in introductory physics students' approaches to problem solving?
- What are the variations in introductory students' conceptual awareness?

As this chapter is the first to discuss the interviews I will take this opportunity to explain in detail the process of analysis which was carried out in order to constitute the categories of

description, focusing specifically on variation in approaches to problem solving as the object of analysis. The findings from this analysis are then presented as categories, followed by a discussion of the structure of the categories and the chapter concludes with a discussion of these findings with respect to relevant literature in the area.

5.2 Interview data analysis process

The data from the interviews were analysed in an iterative process which I began by reading the set of interview transcripts a number of times from start to finish, until I was relatively familiar with the set of transcripts; each time reading the set of transcripts with a different focus in mind. For example, one time I may have been focused on how the students approached the problem, another time paying careful attention to aspects of the problems that the students focused on and yet another time focusing on the variations in the students' approaches to particular problems. The next step was to make summary notes of each of the transcripts, highlighting and recording all information that I perceived to be critical to the students' approaches to problem solving. While making the notes I endeavoured to discover the 'how' and the 'what' aspects within the students' responses, i.e. how is the explanation given? And what is focused on?

After this stage I had up to two pages of notes for each transcript and I then began looking for similarities and differences between the notes, however at all times I was surrounded by the whole transcripts (literally), which I constantly referred back to. On the summary notes I highlighted cases of agreement and underlined cases of critical variation within what I discerned to be the important aspects of the approaches to problem solving and I then endeavoured to physically group the pages of notes and transcripts together or near each other depending on the similarities and differences between them. This attempt at grouping was difficult and often ineffective, because any one transcript could have been positioned in a number of places, or in other words cases of critical variation existed within individual

transcripts. However, this process further served to highlight the cases of variation and agreement within the pool of meaning by the need to constantly re-structure the physical position of the data. Although it was tempting I did not assign similarities to statements that were simply the same, even though in many cases individuals expressed themselves in similar manners, as the students may have approached the problems in different ways.

In this way it was necessary to explore the meaning, and not just the words, of what an individual was saying. When this occurred I had to go back to the original transcript and read a number of pages both before and after the statement to explore the underlying intention toward the approach. I then began to describe these similarities and differences as they had emerged, focusing one time on the similarities and the next on the differences in order to constitute the meaning and structure of the categories. Although during the early stage of describing the categories my main focus was on a search for holistic meanings within the similarities and differences and searching for aspects of critical variation and themes rather than on the overall structure of the categories.

As I constituted these descriptions I constantly referred to the transcripts to ensure that the descriptions accurately represented the data, while at all times bearing in mind that I was analysing the data in order to discover variations in the ways that these students approached problem solving. As the transcripts contained much more information than that pertaining to the participants' approaches it was important not to get sidetracked, especially as it was my intention to search the same transcripts for variations in students' conceptual awareness at a later date.

During this time I found that I was constantly re-grouping the transcripts, each new reading of the transcripts highlighted something that I had not been aware of previously and this makes sense because each time I read the transcripts the focus of my own awareness was different. In this way I began to constitute the categories, by identifying the critical aspects of approaches which were present in some of the transcripts and not in others and also within individual transcripts. Once tentative categories had been constructed I then began to examine the categories and the transcripts for the structure of the categories, although the structure became more evident through constant re-iteration. In searching for the structural aspects of the approaches I endeavoured to identify what was focused upon within each overall meaning. In other words, I searched for themes of expanding awareness that were present in each preliminary category, although at different levels which served to distinguish between the categories and further identified the hierarchical structure.

Having identified the meaning of the approaches, it increasingly appeared that one description of an approach encompassed another while still having a critically different meaning. As iterations continued the search for overall meaning and structure became intertwined more and more.

For each category that I had constituted I then went back to the groupings of transcripts (at this stage I no longer used the notes) to find cases of both agreement and contrast within the transcripts. This was to ensure that the categories actually did describe the variations in the approaches to problem solving of this set of students faithfully and empirically. Indeed even at this stage a number of the categories had to be reconstituted and redefined, until I

was satisfied that I had a set of internally related categories that represented holistically the variations in these students' approaches to problem solving.

I then shifted the unit of my analysis from approaches to the variations in these students' conceptions of concepts as I wanted to find a description of the conceptual awareness of this set of students after a module of mechanics. I carried out the analysis in exactly the same way as previously, and although I was familiar with the transcripts by now it was strange to read them with a new set of foci. They appeared as different transcripts which indicated to me that I had been faithful to the data previously by focusing only on those areas of the transcripts which were critical to the variations in approaches. Therefore even though I had read the transcripts many times, it required just as many iterations to arrive at a set of internally related categories describing the conceptual awareness state of this set of students.

It was at this stage with Interview set A that I gave a sample of the interview transcripts (12 transcripts) to the two other members of the research group to analyse. One of the members had previously undertaken a phenomenographic research project and the other member had been present at numerous meetings in which we had discussed phenomenography and the phenomenographic process at length. However, we had not discussed the transcripts themselves nor had I given them any indication as to the categories that I had constituted. These researchers analysed the selected transcripts in a similar manner to that described above and hence they each constituted categories of description for approaches to problem solving and the variation in conceptual awareness for that set of students. The three of us then met to discuss our respective categories and we found that we had each constituted

very similar categories however the descriptions varied. Therefore we went through the transcripts together with each person discussing and defending their own categories, while the others played devil's advocate. We did this until we reached a consensus about the descriptions of all of the categories based on the sample of transcripts that I had given to the other researchers.

With these categories in mind I then returned to the full set of transcripts and again went through each transcript to ensure that the categories were fully descriptive of the data. At this stage I made some minor changes until I was confident that the categories represented the full range of meaning within the data. The final stage in the analysis was to choose excerpts and statements from the transcripts which I felt would give substance and support to the categories.

The process of analysing and constituting the categories of description of these students' approaches to problem solving and variations in conceptual awareness took place over approximately eight months, often with rather substantial breaks in between. At times these breaks were forced, due to other work constraints, however at other times the breaks were an intentional respite from the analysis. This in fact aided the analysis because it effectively served as 'fresh eyes' with which to view the data.

5.3 Qualitative evaluation of approaches to problem solving

5.3.1 Context of the interview data

The primary aim of Interview set A was to explore the variations in the participating students' approaches to problem solving and as discussed in Chapter 3, section 3.5.2.2, the third phase of Interview set B was also to explore variations in approaches to problem solving. The purpose of this was to further analyse and explore the variations in students' approaches to problem solving, although I had already constituted categories describing these variations from Interview set A. Therefore when analysing the data from the Interview set B transcripts, with the unit of analysis being the variations in approaches to problem solving, I was aware of the categories previously constituted, although I analysed these transcripts with an open mind and bracketed my knowledge of those categories (Marton, 2008 personal communication). The analysis of Interview set B revealed the same critical variations in describing the students' approaches to problem solving as Interview set A and these are presented as categories of description and discussed below.

As discussed in Chapter 3, twenty-two first year students were interviewed for Interview set A and a further 20 were interviewed for Interview set B and these students were chosen based on their Force and Motion Conceptual Evaluation results. The range of profiles of the students who participated in these interviews can be seen in Appendix E. This is provided as an informative guide to the students who participated, but individual students will not be

referred to in the findings or discussion of findings (other than excerpts which were chosen to support the descriptions of the categories) as the categories describing the phenomena are a description of the relationship between the set of students and the phenomena in question.

5.3.2 Categories of description

The analysis of the interview transcripts revealed the set of categories that describes the variations in the interview participants' approaches to solving quantitative physics problems:

- No clear approach
- Memory based approach
- Unstructured plug-and-chug
- Structured plug-and-chug
- Scientific approach

The categories are all internally related and are described using two components; how do these students approach problem solving and what is the focus of their approach. Each category is then described in some detail, with excerpts from the interview transcripts chosen to support and give substance to the categories. During the discussion of the categories I am referring to myself (sole interviewer) as interviewer, as this is the format I

used in transcribing the interviews. Table 5.1 outlines the categories and the characteristic of the themes of expanding awareness in each category.

Table 5.1: Key aspects in the range of variation in approaches to problem solving

Themes of expanding awareness	Categories				
	No clear approach	Memory based approach	Unstructured plug-and-chug	Structured plug-and-chug	Scientific approach
Analysis of situation	Analysis based on the given variables	Analysis based on previous examples	Analysis based on required variable	Qualitative analysis based on required formulas	Qualitative analysis
Procedure	Proceeds by trying to use the variables in a random way	Proceeds by trying to 'fit' the given variables to previous examples	Proceeds by choosing formulae based on the variables in a trial and error manner	Solution is planned based on the variables and is carried out systematically	Solution is planned and carried out in a systematic manner based on analysis
Use of concepts	Variables are referred to as terms	Concepts are referred to as variables	Concepts are referred to as variables	Concepts are referred to in order to guide the solution	Concepts are referred to in order to guide the solution
Evaluation of solution	No evaluation is conducted	No evaluation is conducted	No evaluation is conducted	Solution is evaluated	Solution is evaluated

As per the phenomenographic methodology outlined in Chapter 3 and the analysis as explained in section 5.2 above, during analysis of the interview data I endeavoured to simultaneously constitute the meaning and structure of the categories of description. The meanings of the categories were discovered through immersion in the data and based solely on the empirical evidence within the transcripts, whereas the structure of the categories was constituted through the empirical evidence of logical inclusiveness and dimensions of variation. Therefore themes of expanding awareness were discovered which served to distinguish the logical structure and highlight the inclusive hierarchy of the categories. The hierarchy within the five distinct categories describing the variation in these students' approaches to problem solving is illustrated below using empirical evidence. The logical evidence for the hierarchy is presented now in Table 5.1 as the themes of expanding awareness and the corresponding aspects in each category which link and distinguish one category from the other. The criteria for these themes was that they were present in each category, in a manner which highlighted the increasing level of awareness yet also served to distinguish each category from each other in a critical manner.

The categories describing approaches to problem solving exhibited by these students are composed of similar components and yet they represent the qualitatively different ways in which these students approach problem solving. In certain cases two categories may have a common component, yet this serves to further define and relate the categories in terms of the variation in the approaches. An example of this can be seen between the *scientific approach* and the *structured plug-and-chug approach* (described below) as in each case students focus on the concepts to guide their solution, however they approach problem solving in different ways.

No clear approach

This approach is taken when the problem is not approached with any sort of strategy as the situation is simply analysed in terms of the variables that are given in the problem. However, within this approach variables are not referred to as concepts, rather they are discussed as unrelated terms or letters as can be seen from the example below. Therefore the focus of this approach is not on the concepts involved, nor is it based on any particular method of solution. When this approach is adopted there is an attempt to manipulate the given variables in a rather random way to give an answer. Within this approach students are generally not faithful to any particular line of reasoning and if the interviewer questions them on a matter they are likely to change their strategy very easily. There is no attempt to evaluate a solution that may be obtained and there is evidence that within this approach there is no confidence in the process or strategy that is employed. For instance, when asked what problem 1 involves one student replied:

Student: *Involves gravity. It will be going, its 9.8 m/s. So it'll be $2 \times 10 \times 9.8$*

When the interviewer asks the student to explain, he replied:

Student: *Its travelling at 9.8 m/s because the rate of acceleration is gravity, is 9.8 and its 10 m, it'd be slightly over 9.8, would it?*

Interviewer: *Because?*

Student: *Because it had 10 m to travel*
(Transcript 11)

A further illustration of this approach is evident as another student attempts to solve problem 1, when she is asked what she believes the problem involves:

Student: *Involves an equation of knowing the weight of the watermelon, which we do, and how high it's going to fall. And then the velocity as it falls and what is the increase in velocity, as it hits the ground.*

Interviewer: *Ok, so what about any acceleration?*

Student: *Well, I suppose the only acceleration there would be is acceleration due to gravity.*

Interviewer: *So knowing that then how would you solve it?*

Student: *I suppose just sub in the values of the weight, the height, the acceleration, the velocity and the initial speed. You sub it all in and find the final velocity.*

Interviewer: *Ok, sub it into what?*

Student: *Newton's equation...law...which is...*

(Transcript 15)

Another simple example of this is shown when a student is asked what she believes the problem involves in Interview set B,

Student: *Acceleration and time, I want to say velocity but they don't give you a velocity so it mustn't be in it.*

(Transcript 38)

Within the *no clear approach* category the focus throughout is on the variables that are given in the problem; there is no awareness of any external influences which may have bearing on the solution of the problem. By external influences I mean laws of physics, concepts which may be inherently present in the situation but not expressly stated and any previously experienced physics problems.

Memory based approach

Within this approach to problem solving the problem is analysed based on situations that have encountered in the past. This is done either by trying to recall the type of equation that should be used or by relating the problem to a similar one completed perhaps in class. This approach involves relating the variables that are given in the problem to formulae that they

believe they can use to solve the problem and the focus of the solution is not based on the concepts that are involved. However, this is based upon the assumption that the problem can be solved in the same way as the previously encountered one. This could be compared to solving by analogy; however the focus is not on the concepts involved but simply the variables in the problem and therefore is not based on a solid representation of the problem at hand.

Again students who adopt this approach are sometimes successful in answering the problem, this time by remembering a process or similar problem that they have encountered. The following excerpts help to illustrate this approach as a student attempts to solve problem 3:

Student: *I think I did this a couple of weeks ago, I just can't remember.*
Interviewer: *Really? And what do you associate it with?*
Student: *What do you mean?*
Interviewer: *You say, "I think we did this a couple of weeks ago". What is this?*
Student: *Ah, really questions to do with cars and buses going up to traffic lights and going as fast as the other, exactly like this but I never liked it*

This student 'remembers' a little later that "the idea" is that both parties must travel the same distance, however she still cannot "remember how to do it".

This particular student illustrates this approach in a subtler manner when attempting to solve problem 1; she indicates that her first thought on the problem is "equations of motion". When asked in what way equations of motion are involved, she replies:

Student: *You have the weight, you have the height, and you're looking to see how fast it is going, for its speed. It's dropped from the building, so it starts off at zero. The force acting on it will be gravity; you're looking for the speed when it hits the ground, so you're looking for the final velocity.*

Interviewer: *Ok, and what would its acceleration be?*

Student: *I suppose you could use $F = ma$ for the acceleration, cos the force would be gravity at 9.8 and its weight would be 2 kg*

(Transcript 17)

This is a typical example of this approach as this student is not linking any of her physics knowledge in her approach in solving the problem; she remembers the need to use the equations of motion and when acceleration is mentioned she remembers that force is equal to mass by acceleration.

In contrast to the *no clear approach* category within the *memory based approach*, while the focus is still very much on the variables given in the problem, there is awareness that the individual has experienced a problem or problems such as this previously. However, this awareness is limited to, say, that particular example and no other procedural or conceptual issues are considered.

Unstructured plug-and-chug approach

Within this approach to problem solving the problem is evaluated by concentrating solely on identifying the variable that is required. When this approach is adopted students relate the variables that are given in the problem to formulae that they believe they can use to solve the problem. This approach involves identifying the variables and equations correctly but not necessarily noticing that the manner in which they are solving the problem is incorrect or does not in fact answer the question. Within this approach there is difficulty when it is necessary to manipulate a formula or combine a number of concepts to solve a

problem. In this category an appropriate formula may be chosen, that could in principle produce a correct answer, but often a correct answer is not obtained. This is mainly due to the incoherency in the structure of the solution. The focus throughout the process is on the variables and there is no attempt to relate the concepts to the variables in order to guide the solution. The students adopting this approach do not make an attempt to evaluate their solution; if they obtain an answer they accept that answer as correct “otherwise it wouldn’t work out.”

The following excerpt is an example of a student attempting to solve problem 1, when asked for her first thoughts, she replies:

Student: You drop the watermelon and it’s accelerating at -9.8 , speed of gravity. And you want to know how fast it is going before it hits the ground, so it’s final velocity. And we have three things, well we have its weight and we have acceleration due to gravity, its initial velocity and distance. So we can get the final velocity.

Another example of this incoherent use of physics knowledge and unstructured approach is evident when a student is attempting to solve problem 3, Interview set A. In this problem the student is trying to figure out how long it will take person 1, “me”, to catch up with person 2, “she/her”. Person 2 is cycling at a constant 15 m/s, while person 1, originally travelling at 10 m/s, begins to accelerate the moment the two cyclists are level.

Student: Right, well if she’s right beside me from that point when I started accelerating, if I’ll have to see how long it takes me to accelerate to 15 m/s, and that’ll be the time then it’ll take to catch up with her and then if I want to pass her I’ll just keep accelerating.

(Transcript 14)

A further example of the unstructured nature of this plug-and-chug approach is shown in the example below as a student is discussing how she will attempt the problem in Interview set B:

Interviewer: What are you thinking?

Student: I don't know, I'm bad at, like, doing this. See I don't know, I was thinking of putting them all into the equations, seeing what I get from that and then see if I can solve it from what I have.

(Transcript 36)

Within the *unstructured plug-and-chug approach* category there is awareness of previously experienced laws of physics in the form of equations and that the variables given in the problem may be related to these laws of physics in some way in order to obtain a solution to the problem. However, this is carried out in a trial and error manner based on the variables given and required by the problem situation. Within all three of the above approaches, the aim is to get a final numerical figure and there is no consideration as to whether this figure is correct or incorrect.

Structured plug-and-chug approach

Within this category the approach to problem solving involves an evaluation of the problem by stating what formulae or the type of formulae will be used to solve the problem. This approach involves relating the concepts to the variables that are involved and identifying the target variable. In this way the solution is planned based on the variables given in the problem and an appropriate formula is sought immediately, thus the variables that are not given, but are needed for a solution to be found are identified. Within this approach

obstacles are often encountered, because although a problem solving strategy is being used, it is based primarily on the variables rather than on a solid analysis of the physical situation. However, the focus throughout the solution process is on how the concepts are related and they use this to guide the solution. Within this approach the solutions are evaluated either qualitatively or by defending/dismissing the numerical value that has been obtained based on an assumption of what the the solution should be.

The following is an excerpt from a transcript in which a student is describing what he believes problem 1 involves:

Student: *Involves u , v , a , s , t . Equations of motion*
Interviewer: *In what way?*
Student: *It's accelerating because it's dropping and its acceleration isn't changing, always constant. We already know we're dropping it, not pushing it. So u will be zero. We know the height, the displacement, we know the acceleration, so by knowing three things and that acceleration isn't changing we can use the equations of motion.*
(Transcript 10)

A further illustration of this approach can be seen in the extract below as a student is discussing how she will proceed in solving problem 3:

Student: *Well she passes, she is going 15 m/s and you are going 10m/s, so you have to, em.....*
Well the distance will have to be the same, the distance travelled, we're going to have u , v , a , s , t for the two of them, where the distances are equal and initial velocity is 10 m/s, final velocity we don't know, no wait, "until you pass her" so the final velocity is the 15 m/s because er stop accelerating once we reach her speed.
All the while is writing
Me Friend
 $u_1 = 10$ m/s $u_2 = 15$
 $v_1 =$ $v_2 = 15$

$$\begin{array}{ll}
 a_1 = 0.25 \text{ m/s} & a_2 = 0 \\
 s_1 = ? & s_2 = ? \\
 t_1 = ? & t_2 = ?
 \end{array}$$

Student: *You're acceleration is 0.25 m/s and the time isThe time will actually be equal, oh wait...*

Student re-reads problem

Student: *Ah I'll get back to that, your friend.... So we don't know the distance and we don't know the times.
The times are obviously...
The distance will be equal, the same, so that's $s_1 = s_2$
And I want one [an equation] that has, want one that has an s in it. We don't want acceleration involved.*

Interviewer: *You don't? For your friend?*

Student: *No cause that. [Points to $a_2 = 0$]*

Interviewer: *Ok, so what are you trying to figure out?*

Student: *I'm trying to figure out the time it takes for me to reach her.*

Interviewer: *Ok*

Student: *[Re-reads problem] Ok so you're moving at 10 m/s, she's moving at 15, then she passes you, then you begin to accelerate and you want to find the time it takes to catch up to her.
 $v = u + at$, you'll catch up to her in that time*

The point of departure with the *structured plug-and-chug approach* category is that the problem situation is analysed qualitatively. However, it is a qualitative analysis based on the required formulae. Within this category there is awareness of laws of physics and strategic approaches required to solve the quantitative physics problem, involving the variables which are related to the situation. The aim within this category is success in solving the problem/s and failure is perceived as being a disappointment to the interviewer.

Scientific Approach

This approach to problem solving involves a qualitative evaluation of the physical situation using reference to the physics concepts involved. When this approach is adopted the concepts that would be involved in solving the problem are identified and the ways in which those concepts relate to the problem are discussed, in a coherent manner. Within this

approach a plan is outlined for solving the problem and then the variables that will be used to find an answer are identified. Within this approach, there exists a familiarity with the equations that are required to solve the problem; there is no need to refer to the equation sheet. The information available is used to solve the problem, but the correct answer may not always be achieved due to either a mathematical mistake or a conceptual problem. The focus throughout the solution process is on how the concepts are related, using this to guide the solution. Interestingly, within this approach a physical representation is drawn only as a visual aid and the majority of the time the qualitative evaluation is relied upon. Within this approach the solutions are evaluated either qualitatively or by defending/dismissing the numerical value that has been obtained based on an assumption of what the solution should be.

The following is a statement which was made after the interviewer asked one student what his first thoughts on problem 2 were:

Student: *Based on the principle of gravity, like gravity is a constant force acting always downwards, knowing this we have a constant acceleration in a single direction, making it a form of linear motion.*

(Transcript 3)

The excerpt below is taken in fact from the same transcript as the student discusses how he will proceed with problem 3.

Student: *Ok so, I'm going at 10 m/s and "your friend is going to pass you"*
Reading the problem again

Student: *Now I guess when it says here that they are going to pass you at what you estimate to be a constant 15 m/s, I'm going., I could take that as she is moving at 15 m/s or I could take it that she is going 15 m/s faster than you. But if I just take it she is going at 15, then the speed difference is 5 m/s. Is it cool if I draw it out?*

Interviewer: *Sure*

Student now draws a simple sketch of the situation

Student: *So then I start to accelerate at a constant, so my acceleration is 0.25 m/s^2 until I catch her, right?*

Interviewer: *Ok*

Student: *So basically I want the distances to be the same and when I pass her, I'm going to be going faster than her. So I can use simultaneous equations to work how long she will be ahead of me. Ok, so if she travels faster, if I pass her at some distance d , her velocity is constant, she is not accelerating so her distance she travels is going to be d and the distance I travel will also be d .*

(Transcript 3)

Within the *scientific approach* category the qualitative analysis is based on the concepts which are related to the situation and there is awareness of laws of physics, strategic approaches and those concepts which are inherent in the situation but not expressly stated. The aim within this category is also to achieve success in solving the problem and there is personal emotional investment in this success or failure.

5.3.3 Summary

These categories were constituted from all of the data from the interview transcripts and therefore the categories represent the 'collective mind' of the students who were interviewed and any single category cannot be assigned to any one student. For example a *scientific approach* to problem solving could in fact incorporate a *plug-and-chug approach* and this was obvious when certain students solved a lower level problem. Generally they

would still analyse the situation to begin with but would then simply choose an appropriate formula and solve the problem. It only became apparent that the students were using a *scientific approach* when they were faced with higher-level problems and a strategic approach was necessary. This is described in more detail in the next section when all of these findings will be discussed.

As can be seen the themes of expanding awareness illustrate the shift from the first category (*no clear approach*) to the fifth category (*scientific approach*), from a limited problem solving approach to a more inclusive 'acceptable' problem solving approach. In the following section I will compare these categories to previous research in the area of problem solving and illustrate how these categories bring new insight into the field of physics education research in dealing with the problem solving state of a set of novice problem solvers.

5.4 Discussion of problem solving categories

To a large extent the categories describing the variations in problem solving approach presented in this study confirm previous research findings that the majority of novice physics students do not approach physics problems in an ‘expert’ manner. For example, Van Heuvelen (1991a) suggests that physicists approach a problem by qualitatively analysing the situation and then constructing a diagrammatical or graphical representation of it. Meltzer (2005) agrees that qualitative representation of a situation is an important factor in problem solving and that introductory students often find it difficult to do this. Only a small number of these students actually attempted to make a diagrammatical analysis of the problems and an interesting finding here was that the students who did draw a physical representation did not do so for all of the problems that they approached. Reif and Heller (1982) suggest that novices rush into solutions by stringing together numerous random equations whereas experts use qualitative arguments before introducing quantitative detail. Chi *et al.* (1981; 2006) discussed the fact that novices approached problems using the elements within the problem as opposed to experts who approached problems using physics principles. All of these characteristics of novice problem solvers are present in the categories which I have constituted from the data; however ‘expert’ characteristics are also present. If we look at Leonard *et al.*’s (2002) table (Table 2.2) outlining the differences between the problem solving behaviours of experts and novices, generally the characteristics regarded as novice can be seen as synonymous to elements of the three lower hierarchical categories I have constituted. That is, problem solving is largely independent of concepts, usually manipulates equations, uses backward-looking

means-end techniques, cannot usually get unstuck without outside help, solving problems uses all available resources and often has only one method of solving a problem. I find the 'solving problems uses all available resources' characteristic particularly interesting as in both Interview sets A and B at least one student verbalised this, "It's hard to think about what you're going to do and then actually do it" (Transcript 33). In fact within the interview data there are numerous individual statements which highlight the 'novice' problem solver, another being: "When it comes to problems I usually think there might just be one or two [equations], but there's always so many more. But I can't get my head around that many equations". However, there are also elements of an expert's behaviour, as laid out by Leonard *et al.* (2002), to be found within the two higher categories of description. For example, 'conceptual knowledge impacts problem solving', 'often performs qualitative analysis, especially when stuck' and 'is able to think about problem solving while problem solving'. Although I do not believe any of the students who participated in this study are experts, I do believe that within the collective mind there are variations in these novice students' approaches to problem solving, which when viewed hierarchically could result in instruction which helps individual students approach problem solving in a more powerful way.

In an effort to compare students' approaches to that of an 'expert', an lecturer from the same institution was interviewed (Interview set A). One of the most obvious points of departure in this interview was the lecturer's tendency to immediately draw a diagram of the physical situation. The lecturer was asked to think aloud as he solved the problem, as were the students who had participated. Another clear difference in the lecturer's approach to most of the students' approaches was that he initially approached the problems using the

concepts involved rather than stating the equations that would be employed. For example, in problem 1, his “first thought” was conservation of energy rather than linear motion equations. It is also interesting to note here that none of the interview participants of interview set A approached problem 1 using conservation of energy. The lecturer explicitly stated any assumptions he was making in solving the problem, for instance again in problem 1:

I'm assuming it's being dropped from rest so you have its potential energy, mgh . I'm assuming that is equal to its kinetic energy just before it hits the ground.

(Lecturer)

Again none of the student interview participants did this; furthermore, many of the students did not pay sufficient attention to the wording in the problems. They approached the problems impulsively, often skimming over them and deciding on an approach before changing their minds about the process repeatedly.

Problem 1 in Interview set A required little problem solving ability in order to solve it and as long as the student understood that the watermelon would accelerate due to gravity and identified the variables of displacement and velocity, they simply needed to choose an appropriate kinematics equation (which is a very simple form of problem solving). Although many students used a trial and error approach with the equations, in most cases they obtained the correct answer.

On the other hand, problem 3 of interview set A required little conceptual understanding in order to solve it. In this case the students had to realise that both cyclists would travel the

same distance in the same time and use simultaneous equations. Therefore this problem may not have been a typical problem that the students would encounter in class. However, when confronted with this problem most of the students did not approach the problem in a structured manner; many simply calculated how long it would take to increase velocity until they had reached the velocity of the faster cyclist while not taking into account that the faster cyclist is moving forward all the time. Of the few students who did recognise that the displacement of both cyclists would be the same, only a small number of students attempted to use simultaneous equations to solve the problem. This problem required a more sophisticated problem solving strategy, as it required students to see the “big picture”. The same can be said for the main quantitative problem from interview set B, which was adapted from problem 3. The problem must be approached as a whole rather than attempting to solve it in parts, but most students approached it by breaking it up into the two cyclists’ independent journeys. This problem posed no difficulty for the lecturer who immediately made a diagrammatic representation of the problem before he qualitatively analysed it and stated the assumptions that he was making. He continued by determining his goal, constructing his plan and finally executing his plan. When he had obtained a quantitative answer, he looked back over his work and the problem itself before concluding that he believed his answer was correct.

As previously mentioned numerous studies have shown that although students can learn to plug values into algorithmic equations, they may not develop the ability to solve more complex problems (for example see: Leonard *et al.*, 1996; Mazur, 1992; 1997; Redish, 2005; Reif & Scott, 1999), and that is corroborated by the results of this study. However, a point of departure within the results of this study is that there are variations within this

'plug and chug' approach and although it may appear that students are all using the same strategy, this may not be the case. A particularly interesting finding that emerged from the analysis of the interview data was that a student perceived as taking a *scientific approach* to problem solving could simply use a plug-and-chug technique for certain problems when appropriate. This means that if a problem only required a student to use a certain formula, then students who could use a *scientific approach* could simply plug the variables into the formula and obtain a correct answer.

This is consistent with the phenomenographic methodology that one category encompasses those categories which are lower hierarchically (Marton & Booth, 1997). This is also consistent with how experts would approach problem solving when they are confronted with a simple algorithmic problem (Larkin *et al.*, 1980). However, students adopting a *scientific approach* are confident, not only in their approach, but in their choice and use of the appropriate formulae. Students who depended predominantly on the plug-and-chug approach could not adopt the *scientific approach* when the plug-and-chug approach was not adequate. The type of problems typical of end-of-chapter problems (Young *et al.*, 1999) and some examination questions could be solved by students adopting a *structured plug-and-chug approach*, as these students tend to use a somewhat strategic approach when solving the problems. However, as the problems become more complex the strategy of simply identifying the correct variables is no longer adequate. Heller and Hollabaugh (1992) among others (Heller *et al.*, 1992; Schultz & Lockhead, 1991) have highlighted the need for students to be able to solve 'real-world', 'context-rich' problems.

The research presented here demonstrates that the majority of students could not solve these problems and verifies that problem-solving skills should be an explicit element of instruction. Hoellwarth *et al.* (2005) discuss the need for students to learn both concepts and problem solving skills and this is tentatively verified within the research shown here but will be discussed in more detail in Chapter 6, following the presentation of the categories describing the variations in conceptual awareness.

Those students who adopted an *unstructured plug-and-chug approach* could attempt the end-of-chapter type problems and may obtain an answer but may not know or recognise that the approach or answer was incorrect and this is also true for those students using a *memory based approach*. However, those students who adopt a *no clear approach* would find it quite difficult to solve typical end-of-chapter problems, as they do not seem to use any coherent knowledge structure or strategy with which to solve the problems.

Tuminaro (2003; Tuminaro & Redish, 2007) describes the ‘epistemic games’ that students play when solving problems, which were developed by observing ‘episodes’ of groups of students as they solved homework problems. These games are couched in three ‘frames’, with a frame being described as the definition of a situation which guides interpretation. These three frames are ‘quantitative sense-making’, ‘qualitative sense-making’ and ‘rote equation chasing’. Although the emphasis of Tuminaro’s categories is on the students’ use of mathematics in their approaches to problem solving, many similarities can be drawn between those ‘epistemic games’ and the outcome space of problem solving approaches presented here. The ‘mapping meaning to mathematics’ game can be closely compared with the *scientific approach* constituted from this data and likewise the ‘mapping

mathematics to meaning' can be compared with the structured plug-and-chug category. The game 'pictorial analysis' is not specifically related to any single one of the categories presented here, however the 'recursive plug-and-chug' game is closely related to the unstructured plug-and-chug category. Interestingly the lowest hierarchical epistemic game 'transliteration to mathematics' can be compared to the memory-based approach in that the students approach the problem by trying to find a solution pattern that seems to match the current problem. Although it was not the intention of the research presented here to investigate students' use of mathematics, but to present a set of categories which allowed for a better description of novice problem solvers, the results produced by both sets of research serve to imply that these categories could be used to track students progress during a typical year of study of introductory physics.

5.5 Chapter summary

These categories describe the problem solving approaches of a set of novice problem solvers. None of these students could be categorised as experts as much more than a strategic approach is expected from an expert problem solver (Schultz & Lockhead, 1991). However, the result of this study is an outcome space that allows for a better description of the problem solving approaches of a class of students. Students must learn how to become more 'expert-like' through instruction helping them to discern critical aspects of a problem situation and thereby develop the capability to approach and solve novel and complex problems.

CHAPTER 6

VARIATIONS IN CONCEPTUAL AWARENESS

6.1 Introduction

As discussed in the previous chapter, although one of the main aims of interview set A was to investigate students' approaches to solving quantitative physics problems in a number of contexts, a second aim was to use the interview data to examine the variations in the students' conceptual awareness based on their discussions of the concepts involved in solving the problems. This was possible due to the 'think aloud' nature of the interviews, and the fact that I asked all students to explain and justify each step they were taking in solving the problems. To clarify, conceptual awareness used in this context refers to a conceptualisation of knowledge rather than a discussion of understanding or knowledge of specific concepts.

The first two problems in the interview could be solved quite simply using one or more of Newton's equations of linear motion but because the interviewer probed the students' reasoning as they attempted to solve the problems it was possible to obtain valuable information about the variations in these students' conceptual awareness within the context of a physics problem solving situation. The process of analysis was the same as that described in detail in Chapter 5, section 5.2.

6.2 Qualitative evaluation of conceptual awareness

6.2.1 Categories of description

A set of categories emerged from analysis of the data, which described the variations in conceptual awareness among these first year students.

- Words to numbers
- Terms to concepts
- Concepts to concepts
- Concepts to world

Again these categories are internally related and represent the ‘collective mind’ of the students as they are based on simultaneity, variation and discernment. Each category is described below in some detail based on the empirical data within the transcripts, with excerpts from the interview transcripts which were again chosen to support the categories. As before, during the analysis of the data from the interviews, I endeavoured to co-constitute the meaning as well as the logical and empirical structure of the categories. I searched for themes of expanding awareness that were present in the data which served to distinguish the aspects of critical variation and highlight the structural relationship of the categories. The four distinct categories which describe the variations in the students’ conceptual awareness are related in an inclusive hierarchy, increasing in completeness. The

descriptions of the categories are presented to illustrate the empirical evidence for the hierarchy. In Table 6.1 below I outline the logical evidence for the inclusive hierarchy by stating the themes of expanding awareness and the corresponding aspects in each category which link and distinguish one category from another.

Table 6.1: Key aspects in the range of variation in conceptual awareness

Themes of expanding awareness	Categories			
	Words to numbers	Terms to concepts	Concepts to concepts	Concepts to world
Conceptualisation of concepts	Concepts represent words used in physics class	Concepts represent variables which are given in certain situations	Concepts represent physical entities which may be related to one another	Concepts represent physical entities which are related to one another
Use of concepts	Physical situations occur, conceptual terms should then be assigned	Conceptual terms aid solution rather than explain situation	Conceptual terms explain why and how things happen	Concepts explain why and how things happen
Explanation of concepts	No explanation of concepts is provided	Explanations of concepts are context dependent	Explanations of concepts appear to be context dependant	Explanations of concepts are not context dependent

Words to numbers

Within this category the physical situation is discussed using terms which may or may not be related to the situation. In this category there is either very little or no understanding of the concepts involved and although the concepts and terms may be named there is no organisational structure with which to use the knowledge. Within this category velocity and acceleration may not necessarily be confused for instance as there simply does not appear to be a mental model for what either of these terms is. An example of this comes from a transcript in which the student suggested that “acceleration is the same as velocity; it’s just not in a given direction”. The focus within this category is numerical rather than conceptual, that is, within this category words are linked to numbers.

Further illustration of this category is illustrated below as a student discusses problem 1:

- .
- Student: *Involves finding out the acceleration, force is mass by acceleration, so if you find acceleration, you find the force.*
- Interviewer: *Ok, so what are you actually asked?*
- Student: *You’re actually finding the acceleration*
- Interviewer: *So if I asked you what force is acting on the watermelon as it is dropping?*
- Student: *Gravity*
- Interviewer: *Ok, so what’s the acceleration?*
- Student: *Its gravity, it’s the... force divided by the mass*
- Interviewer: *What is the force?*
- Student: *Its 2 kg, no sorry 9.8 / 2*
- Interviewer: *Is 9.8 a force*
- Student: *Yeah I would say so*

(Transcript 20)

The student continues to include the mass in his attempt to calculate the “speed” of the object, so the interviewer asks the student what he thinks would happen if two objects of

mass 2 kg and 50 kg were dropped at the same time. At this point the student laughs and says:

Student: *Well I found out since that they reach the ground at the same time, but I wouldn't have thought that. Seemingly gravity acts on the two of them at the same time.*

(Transcript 20)

Another example of this category occurs again with question 1; this student's first thought on the problem is to make sure all the variables are in the right units.

Student: *How fast it's going is gonna be its mass by height or distance*

(Transcript 8)

At this point the student looks at the equation sheet and continues:

Student: *Velocity is gonna be its distance over time, so you don't know time, so we're gonna have to say...
In order to find the time you're gonna have to know the acceleration though because you've got a certain distance and you know the weight. So if you knew the acceleration, then you'd know how fast that weight is going compared to each section of time, then you could find your speed.*

(Transcript 8)

Within the *words to numbers* category the focus throughout is solely on the numerical terms which are used within the problem situation and there is no awareness of how these terms may be related to one another in any structured sense. Within this category it is proposed that terms and the numerical variables in any given situation may be confused, for example, an acceleration of 5 m/s^2 may be discussed as having the characteristics of speed.

Terms to concepts

Within this category of conceptual awareness the physical situation is discussed using concepts that may or may not be related to the situation. The distinction between different concepts is not clear and the concepts have the role of aiding in the solution rather than explaining variations in the situation. The focus within this category is on the variables in any given situation and the manipulation of these to solve a problem. Explanations of the concepts are context dependent, and the vectorial nature of concepts is ignored.

Student: *Involves net forces or I suppose use linear equations because it's travelling straight down.*

(Transcript 6)

The interviewer then asks this student to describe how he will go about answering the problem.

Student: *So it's going to start off at zero, initial velocity of zero until you drop it. Then you can calculate its acceleration, you have a mass. So you can find the force by $F = ma$ (writes $F = (2) (9.81)$) That's the force that will be applied all the way down, or that's the force it will have when it's dropping.*

Interviewer: *So how will you use that to find how fast the watermelon is going?*

Student: *Maybe, just on the linear equations, if we have the displacement, we have its acceleration, have its initial velocity, then we want its final velocity. But the mass thing, the way it gives the mass, because it's going to keep constant, all the questions we've done didn't really have the mass.*

(Transcript 6)

It is interesting to note here that this student continued the solution of this problem by selecting an appropriate equation and obtaining the correct answer.

Within the *terms to concepts* category the focus again is on the variables within the problem situation, but these variables represent conceptual terms which may be manipulated within an equation to arrive at a numerical solution. Within this category, the perception is that as long as there are variables which can be used in a given equation then that equation must be the correct one to use, that is, the concepts must fit the chosen equation. There does not appear to be awareness of how the concepts are related to each other or that they can explain the physical situation as it occurs.

Concepts to concepts

Within this category the physical situation is explained based on the concepts that are believed to be involved and how those concepts are related to the situation at hand is discussed, in a coherent manner,. Concepts are related to each other but this relationship is causal rather than inherent.

Student: *Involves free-falling objects, from a certain height. All objects fall at the same rate, accelerating at 9.8 m/s^2 , if you could find the time, you could find the velocity.*

(Transcript 2)

Therefore the focus of this category is on the particular concepts that are perceived as being related to the situation and other concepts are ignored. Conceptions of particular concepts within this category are more context dependent than in the category below, and although concepts such as velocity and acceleration are not confused, there is a tendency to depend on the formulas rather than using an understanding of the concepts. The following excerpt is a clear example of this when this student is discussing his solution of problem 2, he

realises he has been solving the problem without factoring in displacement and thus he discards his original method.

Student: *I think I've made a big mistake; I've left out the distance it travels, so I used the wrong formula.
I think what I should have done is notice that it factors in the distance it travels, so I'd say if I used another formula like, $x = v_0t + \frac{1}{2}at^2$, that way it factors in the distance as well.*

(Transcript 2)

Within the *concepts to concepts* category the focus is on the particular concepts which are perceived as being present within the problem situation; however there is no awareness of how other concepts may be related. The conceptual terms are discussed and related to the situation in order to explain the situation. However, these discussions appear to depend on the context at hand.

Concepts to world

Within this category physical situations are explained based on the concepts involved and how the concepts relate to each other and to the situation at hand are discussed in a coherent manner. Numerous concepts are focused upon simultaneously in order to explain the situation or the steps involved in solving a problem. The vectorial nature of concepts such as velocity, acceleration and displacement is also a focus of this category. The explanations of the concepts do not appear to be context dependent as they are consistent over a range of situations.

Student 4 below describes why problem 2 can be answered using the principle of linear motion:

Student: *Travels straight up, travels straight down, the only acceleration being felt by the ball, well after it leaves your hand, is -9.81 so it meets the requirements of linear motion.*

(Transcript 4)

This particular student also correctly identifies that the displacement is not the distance travelled and that it is simply a change in position of 2 m in the negative direction.

The point of departure in the *concepts to world* category is that numerous concepts may be focused upon simultaneously and there is awareness of how these concepts are related to the situation and to each other. Explanations of the concepts and conceptual terms are consistent over a range of situations.

6.2.2 Summary

Again these categories were constituted using all the data from the interviews and they represent the variations in these students' conceptual awareness. Although any one student's conceptual awareness could not be entirely described by any single one of these categories, the hierarchical structure of the categories provided by the empirical evidence appears to illustrate that the *concepts to world* category would be most desirable. As is illustrated by the themes of expanding awareness there is a logical and inclusive shift in conceptual awareness from the first category to the final category, with category *concepts*

to world being the highest hierarchical category due to the holistic nature of conceptual awareness represented within it. In the next section I will discuss this qualitative evaluation of conceptual awareness in terms of previous research in the area.

6.3 Discussion of the variations in conceptual awareness

Looking at the categories that describe the variations in conceptual awareness, it is clear that there is a range of conceptual knowledge that students draw upon when faced with a physical situation or problem. The findings reveal indisputably that some students have undifferentiated concepts of velocity, acceleration and force and this agrees with a large amount of research carried out in this area (for example see: Clement, 1982; Finegold & Gorsky, 1991; Halloun & Hestenes, 1985a; Sharma & Sharma, 2007; Trowbridge & McDermott, 1981). This also agrees with results from the FMCE, as the overall low score on questions involving acceleration and forces implies that students are not gaining the conceptual understanding necessary to discriminate between these concepts. Another area of conceptual difficulty is the distinction between displacement and distance as well as incoherent or non-existent concepts of vectors in dynamics. A large number of students had difficulty with vectorial nature of the concepts and some students would incorporate vectors in their problem solving only depending on the context of the problem. For example, student 4 assigned a positive value to displacement in problem 1 and a negative in problem 2 even though the displacement was in the same direction in both problems. Students often labelled acceleration due to gravity as a negative figure but always took velocity as positive. Again this appears to agree with a large amount of research which has investigated students' difficulty with the use of and concepts of vectors within a mechanics setting (for example see: Aguirre & Erickson, 1984; Aguirre & Rankin, 1989; Nguyen & Meltzer, 2003; Shaffer & McDermott, 2005). Hestenes and Halloun (1995) suggest a three-stage

model of conceptual evaluation, whereby at stage 2, a student has developed coherent dynamical concepts that include vectorial concepts of velocity and acceleration.

It is obvious that the category *concepts to world* represents a more powerful structure of conceptual awareness than the other categories as within this category students appear to have the ability to discern numerous critical aspects within a situation simultaneously. Therefore not only is there awareness and understanding of the individual concepts, there is also the capability to do something with that understanding, i.e. explain a physical situation. Although the situations that these students were presented with were relatively simple, it is the capability to deal with a novel situation using the knowledge that the individual has that is important (Marton & Booth, 1997). In fact, during his keynote address at an EARLI sig 9 meeting in May 2008, Ference Marton suggested that developing the capability of making sense of novel situations in powerful ways was the most important indirect object of learning. Sabella and Redish (2007) state that although the conceptual knowledge itself is an integral part of what students need to learn when studying physics, it is just as important that students know when and how to use this knowledge.

On the other hand the category *words to numbers* perhaps represents the conceptual awareness that we would expect from students who have received no formal instruction in mechanics. However, being a teacher myself, and after examining evidence from previous studies it becomes obvious that the conceptual knowledge of many introductory physics students' could be described by this category – even after formal instruction in mechanics. For example Halloun and Hestenes (1985b, pg 1059) discovered that after instruction, although students had “rote knowledge” of physical laws and terms, explanations were

either non-existent or determined to be “prescientific”. While, Halloun and Hestenes label these explanations as common sense beliefs I would argue that they are particular ways of seeing the phenomenon made up of both formal and informal interpretations of experience. These ways of seeing are based on the aspects of previous experience that the students have been focally aware of, both in a formal educational sense and an informal ‘everyday’ sense.

As the focal awareness within the category *words to numbers* is on the numerical terms which are presented in the problem situation there is no room for discerning the critical features within the situation, which is apparent as the meaning of the problem is often lost within this category. More than this though, the conceptual terms themselves hold no significant meaning within this category so therefore it would seem as though the possibility for conceptual understanding is suppressed. Therefore it appears that instruction in physics should enable students to perceive the significance of the conceptual nature of their studies. This is supported by a wide range of studies which argue that conceptual understanding should be an explicit part of physics instruction (For example see: Trowbridge & McDermott, 1981; McDermott *et al.*, 1987; Mazur, 1992; Ambrose *et al.*, 1999; Kim & Pak, 2002). Although the intentions within many of these calls for conceptual instruction were to overcome stable misconceptions, the fact remains that the students who participated in the studies referred to here either could not explain physical situations as they occurred or solve quantitative problems they were presented with.

The fact that learning is contextual is demonstrated here, as it has been demonstrated elsewhere and this is one of the tenets of phenomenography (Bowden *et al.*, 1992). Some students treated the same problem in different ways and many students demonstrated

different understandings of the same phenomena in different contexts. This can be seen to a lesser and greater degree within the categories ‘terms to concepts’ and ‘concepts to concepts’; as conceptual awareness becomes more complete, explanations of individual concepts become less context dependent. This variation in context dependence was observable for two reasons: first the interviews consisted of a number of qualitatively different problems, which required students to describe the same phenomena in different contexts and second because the categories describing the variations in conceptual awareness were constituted from all of the data from these interviews.

These variations in conceptual awareness go some way to explaining the findings from the FMCE, as presented in Chapter 4. The findings showed that the majority of students did not conceive of mechanics in a Newtonian manner and this could be explained by the fact that many students’ have not learned to perceive the conceptual nature of physics, regardless of the specific concepts being addressed.

6.4 Summary

The categories ‘terms to concepts’ and ‘concepts to concepts’ appear to represent intermediate levels of conceptual awareness, which, when viewed in conjunction with the set of categories helps to tell the story of the possible progression in conceptual knowledge from an extremely limited state to a more inclusive ‘acceptable’ state. It is possible that these categories could represent stages of conceptual knowledge development, however this could only be verified through a longitudinal study. This type of variation in conceptual awareness within a collective situation has not been well documented in the past and the categories presented here highlight the expanding awareness of the significance of the conceptual nature of physics. Therefore through this expanding awareness we see an expanding level of understanding of the specific concepts involved in the situations, how they are related to each other and how they are related to the whole situation.

6.5 Relationship between conceptual awareness and problem solving

During analysis of the interview data I assumed that there was an internal relationship between conceptual awareness and approach to problem solving. This is a major tenet of phenomenography; a person's awareness is structured by the entirety of their experiences and although the person will be focally aware of different aspects of a situation at any given time, there cannot be an external distinction between one type of knowledge and another. However, it is how this internal relationship affects activity and outcome that is being investigated here.

As stated previously, during the analysis of the transcripts the categories were constituted from all of the data from the interviews and no one student can necessarily be described by a single category. However, once analysis was complete and the stable categories were constituted it was possible, for illustrative purposes, to place individual transcripts within the category that most identified the transcript with regard to conceptual awareness. Having done this I then examined the transcripts using the themes of expanding awareness and discovered the relative approaches to problem solving which were most evident. The result of this is shown in Table 6.2 below but individual categories describing approach to problem solving are not represented because it was not possible to definitively place the transcripts in a particular category. Instead the *memory based* and *unstructured plug-and-chug* categories are grouped as 'quantitative analysis & unsystematic approach' and the

structured plug-and-chug and *scientific* categories are grouped as ‘qualitative analysis & systematic approach’.

Table 6.2: Relative number of transcripts in each category for Interview set A

Categories of description	Words to numbers	Terms to concepts	Concepts to concepts	Concepts to world
	No. of transcripts in category type			
No clear approach	4			
Quantitative analysis & unsystematic approach	6	7		
Qualitative analysis & systematic approach		2	2	1

An examination of Table 6.2 clearly shows that the majority of students from Interview set A approached problem solving in an unsystematic manner and that these students’ conceptual awareness could be described by the lower two hierarchical categories describing the variation in conceptual awareness.

Heller *et al.* (1992) suggest that many students in introductory physics courses view problem solving as independent of the physics concepts being taught and this view was reiterated by a number of the students that were interviewed for this study. Students stated that they could understand the concepts but not the “maths” and vice versa. However, findings from this study reveal that students who have a more coherent conceptual framework approach quantitative problems in a more structured manner. However, these

students do not necessarily approach the problem as a scientist would and this can cause difficulty when the problem requires a more qualitative approach.

Findings from this study reveal that students can solve the standard textbook problems without having a coherent understanding of the concepts involved, consistent with a great deal of previous research (for example see: Clement, 1982; McDermott, 1984, 1991; Bowden *et al.*, 1992; Hestenes *et al.*, 1992). This finding is one of the reasons that physics education research began. All of the students obtained a correct answer for problem 1 in interview set A, however as the problems became more context-based the students who did not have a coherent understanding of the concepts could not apply their knowledge to solving the problem. One interesting factor, which was not considered before the interviews, is that students could generally solve the problems without any vectorial understanding of velocity and acceleration. The difficulties arose when students used vectors some of the time, in certain cases a student would obtain a negative value for displacement or velocity and simply dismiss it or begin the process again believing he/she had made a mistake.

However, another finding reveals that in certain cases, although a student may have somewhat structured conceptual awareness they may not be able use their knowledge to solve a problem that they have not encountered before. Sabella & Redish (2007) agree with this when they suggest that although conceptual knowledge is an essential part of learning physics, students need to know how and when to use that knowledge. This became very apparent when students attempted to solve the quantitative problem in Interview set B; the students were unable to “see” how to solve the problem using the knowledge that they had. Many students who showed a coherent understanding of the concepts of displacement,

velocity and acceleration still could not apply this knowledge within the novel situation they were faced with.

6.6 Chapter Summary

By examining the categories of conceptual awareness presented in this chapter, it is apparent that the category *concepts to world* represents the most powerful state of conceptual awareness and it is argued here that unless a student's conceptual awareness can be described by the category *concepts to world*, novel problem solving is very difficult. In order for students to become adept problem solvers it appears that it is necessary for them to first be aware of the conceptual nature of physics. Through this awareness it is more likely that they will have the capability to simultaneously discern the critical features of a problem situation and approach the problem in a powerful manner.

CHAPTER 7

VARIATIONS IN CONCEPTION OF ACCELERATION

7.1 Introduction

The previous chapter discussed the variations in students' conceptual awareness as a whole and although the findings suggest that within the highest hierarchical category there is evidence of a more powerful understanding of specific concepts, this does not give much indication about the variations in students' understanding of particular concepts. Therefore, in an attempt to understand the variations in how these students understood a particular concept in mechanics I used and analysed specific questions within the interview (Interview set B) to discover the variations in the students' conceptions of acceleration. I chose the concept acceleration because it is a critical and fundamental concept in mechanics, which may also be seen as representative of a concept which causes difficulties for students beginning to study physics.

7.2 Interview data analysis process

The data for these interviews was analysed in the same iterative manner as in Interview set A (section 5.2). Again the first step was to take the phenomenon, the conceptions of acceleration, and read the set of interview transcripts from start to finish a number of times. Each time I did this with a different focus in mind while at the same time searching for information related to the students' conceptions of acceleration. Again I made summary notes for each transcript recording what I perceived to be the critical aspects concerning that perception. I then went through the notes highlighting similarities and underlining variations in the same manner as I had done for previous objects of analyses. Again I went through numerous processes in which I physically grouped the notes and transcripts near or on top of each other based on those that I perceived to be similar to each other.

After I had attempted to describe these similarities and differences as they had emerged I then began to constitute the categories of description. I examined the set of transcripts for themes and the overall meaning of acceleration for these students, and then I examined each transcript for cases of critical variation within these themes. In doing this I alternated between examining the transcripts as a set and examining each individual transcript, searching for themes and searching for structure within these themes. Again this involved numerous iterations with the categories constantly being revised and restructured until I finally felt confident that the set of categories accurately represented all the data and together were a description of the variations in these students' conceptions of acceleration.

Once this was accomplished I then sought excerpts and statements from that data that I felt supported the categories of description.

7.3 Qualitative evaluation of conceptions of acceleration

7.3.1 Categories of description

This set of categories describing these students' conceptions of acceleration was constituted from the analysis of all twenty transcripts resulting from Interview set B. Again the categories are all internally related and are described using two components; how acceleration is described and what is focused on. In the same way as for the previous outcome spaces, the set of categories represent the collective mind of the students who participated and therefore no student can necessarily be situated in any one category. The categories are described in some detail below, based on the empirical data within the transcripts, with the aid of extracts from the interview transcripts and, as in the previous chapters concerning outcome spaces, the logical structure within the categories describing the variations in students' conceptions of acceleration was discovered using empirical and logical evidence in the form of themes of expanding awareness. For this unit of analysis, more than any other, I found it necessary to bracket my own perceptions of acceleration in order to faithfully constitute categories describing the variations in these students' conceptions making the process perhaps hence more difficult than previous analyses. This was especially the case when searching for the logical structure of the categories while I ensured that any structure that I proposed was confirmed by empirical evidence from the data. Meaning that, for each category, at least some of the transcripts from which the category was constituted showed some reference to aspects of the conception that were

present in categories lower in the hierarchy, but not the other way around. Table 7.1 illustrates the logical evidence for the inclusive hierarchy of the categories by presenting the themes of expanding awareness and the corresponding critical aspects which serve to link and distinguish one category from the other.

Table 7.1: Key aspects in the range of variation in perception of acceleration

Themes of expanding awareness	Categories					
	1	2	3	4	5	6
Description of acceleration	New or unconsidered term	Rate of change of displacement	Change in speed	Causes a change in velocity	Rate of change of velocity, with vector problems	Rate of change of velocity
Relationship to force	Non related	Non causal	Causal, non linear relationship	Acts the same as force	Causal but depends whether motion is with or against force	Causal, linear relationship
Discussion based on	Object in question	Velocity of object	Direction of the motion	Effect that acceleration has on object	Direction of motion of the force	Change in velocity due to force

Perception of acceleration category 1

Within this category acceleration is an unconsidered term. Acceleration and speed are described as meaning the same thing, but there is a distinction between speed and velocity. Acceleration may be described as being related to force but many things can constitute a force. The focus of this category is on the object in question and there is evidence that all terms are used interchangeably.

The following are excerpts during which the students are describing the motion of the pen after it has left the interviewer's hand.

Student: *Velocity is speed in a certain direction and then acceleration is just kind of the speed of a moving object.*

Interviewer: *Is there a force on it?*

Student: *Yeah the direction of the velocity.*

(Transcript 39)

Interviewer: *Where does the acceleration come from?*

Student: *The ... is it the potential energy? Like there is potential energy from your hand pushing it up?*

(Transcript 23)

Within category 1 the focus of the perception is on the object which is experiencing the motion and there is either no or very limited awareness of the formal term acceleration. It is proposed that within this category explanations are based on random terms which have been encountered but hold no conceptual significance.

Perception of acceleration category 2

Within this category acceleration and velocity are described as meaning the same thing. If velocity is observed to be increasing or decreasing, acceleration is also described as increasing or decreasing respectively. If an object is at rest it has zero acceleration and a constant velocity indicates a constant acceleration. Acceleration may be the result of a force, but a force does not necessarily result in acceleration. Also within this category speeding up is the result of an increasing force. The focus within this category is on the velocity of an object.

This is highlighted further in the following example; the student is again describing the motion of the pen as it leaves the interviewer's hand:

Student: *When you throw it up its losing acceleration because of the force of gravity going against it and it gets to a point where it reaches nought and just stops still. And then its, em, it has potential energy because it's a certain distance off the ground. The potential energy then kind of falls again and it starts accelerating, by the time it gets to the ground again.*

At another point in the interview as this student is discussing possible forces on an object moving at a constant velocity, the interviewer asks him if an object is moving with constant velocity, what does that mean about the acceleration, he replies:

Student: *The acceleration is constant*
(Transcript 40)

A similar example comes from an excerpt of another transcript as the student is discussing constant velocity and acceleration:

Student: *Because if the ...if the acceleration is cons...for the acceleration or for the velocity to be constant, the acceleration has to be constant as well.*
(Transcript 23)

Within category 2, although there is awareness of the term acceleration this awareness is focused on the acceleration of an object behaving in exactly the same manner as the velocity of the object. Therefore a force has the effect of changing the acceleration in the same way as it would change the velocity of an object.

Perception of acceleration category 3

In this category acceleration is described as acting the same as velocity but means speeding up or slowing down. However, if an object is speeding up it has a positive and increasing value of acceleration and if an object is slowing down it has a negative and decreasing value of acceleration. Acceleration is caused by force e.g. gravity; however it may not be a proportional relationship. For example, gravity is only force acting down but acceleration is increasing or there is a constant acceleration due to an increasing force. In this case zero acceleration is caused by forces in 'equilibrium'. The focus within the category is on the direction of the motion of the object. The following is an excerpt from an interview in which the student has just said that acceleration is "increasing, it's accelerating" as the pen is falling back to the ground, the interviewer then asks the student about the acceleration as the pen is travelling upwards, he replies:

Student: *The acceleration is a minus, it's slowing down.*

Interviewer: *So is it a constant acceleration, an increasing acceleration or a decreasing acceleration?*

Student: *It's decreasing.*

Interviewer: *Decreasing acceleration?*

Student: *Yeah, it's not constant.*

When this student is asked about the acceleration as the pen falls, he replies:

Student: *The acceleration is increasing ... due to gravity I think*

The interviewer then asks him to explain this and he responds:

Student: *The object will move faster the further it falls..
Rather than falling at a constant speed. So if you dropped it from higher by
the time it reached the ground it would be going faster.*
(Transcript 32)

The following is a reply from another student who was also asked the same question, but this time regarding the acceleration of the pen on its journey upwards:

Student: *Its decreasing... cos its gonna get slower and slower*
(Transcript 24)

Finally the excerpt below is from a student who is asked what kind of force would be required make the block speed up at a steady rate with constant acceleration:

Student: *An....increasing force.*
Interviewer: *Why would you say it's an increasing force?*
Student: *Cos it's accelerating*
(Transcript 36)

Within category 3, acceleration is perceived as the slowing down or speeding up of an object. However, the focus is on the direction of motion of the object and the sign of acceleration changes with the direction.

Perception of acceleration category 4

Within this category acceleration is described as acting like a force and there is a distinction between acceleration and acceleration due to gravity. Acceleration due to gravity within this category is down and constant and therefore a constant force results in constant acceleration. The focus of this category is on the effect that acceleration has on a body. This category only applies in a context with perceived gravity.

An example of this can be seen in the following excerpt as the student discusses the motion of the pen:

Student: *Acceleration due to gravity is acting on it, so its velocity is decreasing as it moves up. And then when the pen moves down, when the velocity is eventually counteracted by the acceleration due to gravity, it moves downward and it accelerates.*

When asked specifically about the acceleration of the pen, the student replies:

Student: *Its acceleration is constant, whether it's moving up or down.*

Interviewer: *Why do you say it is constant?*

Student: *Because it's always, acceleration due to gravity is always -9.81 m/s^2*
(Transcript 29)

Another illustration of this category is shown below; the student is discussing the motion of the pen as it rises:

Student: *The speed is rising to a point and then it stops the acceleration due to gravity makes the pen fall at a constant acceleration.*
(Transcript 23)

Within category 4 there is awareness of acceleration as a change in velocity but the distinction is that acceleration due to gravity causes this change in velocity, that is, an object's motion will be changed by acceleration due to gravity. Therefore the focus within this category is on the effect that acceleration has on a body.

Perception of acceleration category 5

In this category acceleration is described as the rate of change of velocity and therefore zero acceleration results in a constant velocity. Within this category a constant acceleration is the result of a constant force however acceleration is positive or negative depending on the direction of the force relative to the motion of an object, i.e. whether motion is going 'with' or 'against' force. Negative acceleration means velocity is decreasing and positive acceleration means velocity is increasing. The focus within this category is on the direction of motion relative to force.

The following excerpt is taken from a transcript in which the student is again explaining the motion of the pen as it leaves the interviewer's hand:

Student: *Well you give it momentum first of all, and then gravity is pulling it down all the time, em, it pulls it down until, like it accelerates at -9.81 m/s^2 until it gets to zero velocity and then gravity starts acting in the positive direction on it.*

The interviewer then asks the student to explain this further, inquiring about the acceleration of the pen at the highest point in its journey, the student replies:

Student: *It's ...9.8, isn't it?*
Interviewer: *Ok and you're not too sure?*
Student: *Well, it is because It's not acting against gravity anymore, like it might not have a velocity yet but it still, gravity is still going to ... [pushing down with his hand]*
Interviewer: *Ok and then on its way back down?*
Student: *9.8*

A little later in the interview, the interviewer again asks for clarification about the acceleration at the highest point, the student replies:

Student: *Well, the velocity is zero but the gravity [means acceleration] is the same, it's at 9.8. Well it's kind of acting in the positive, because it's not going, like It's, has no more, like it's not going against gravity anymore.*
(Transcript 33)

The point of departure within category 5 is that there is awareness of acceleration as meaning the rate of change of velocity and this change in velocity is caused by an external force. However, the focus is on whether the motion is 'going with' or going against' said force.

Perception of acceleration category 6

Within this category acceleration is also described as being the rate of change of velocity, and hence if a body is accelerating its velocity is changing at a rate equal to the acceleration; zero acceleration results in a constant velocity. The point of departure with this category is that a constant acceleration is the result of a constant force and the direction of acceleration will be in the direction of the force. The focus of this category is on the change in velocity as a result of a force and hence an acceleration.

The following excerpt is from a student when he was asked what force would speed up a block on an ice rink at a constant rate;

Student: *If it's speeding up at a constant rate it has to be a constant force.*
Interviewer: *Why?*
Student: *Because if it has a constant acceleration it has to be a constant force providing that constant acceleration.*

(Transcript 41)

Another illustration of this category is taken from the first of the conceptual questions; this student was asked to describe the motion of a pen as it left the interviewer's hand:

Student: *So there is a positive velocity and the negative acceleration caused by the force of gravity*

(Transcript 31)

Within category 6, acceleration is perceived as the rate of change of velocity and there is awareness that acceleration in a certain direction is the result of a force in that direction. Also within this category there is a coherent understanding of the vectorial nature of acceleration.

7.3.2 Summary

Together these categories represent these students' experience of acceleration; they describe the variations in how the students conceptualise acceleration particularly in

relation to force and velocity. As with the other outcome spaces they represent the collective mind of the students who participated in the interviews. The themes of expanding awareness highlight the logical and inclusive shift from an incoherent perception of acceleration in category 1 to a coherent perception of acceleration in category 6, which we as physicists have come to accept as the 'correct' perception of acceleration. However, categories 1 – 5 cannot be termed 'misconceptions' as these categories represent the collective mind of the students who participated. It is clear that categories 1 to 4 describe perceptions of acceleration which are context dependent, whereas categories 5 and 6 appear to be much less context dependent. These categories describe the critical variations in how the concept of acceleration is perceived by this group of students and no individual student could be assigned to one particular category. In the following section I will discuss how these categories, describing variations in the conception of acceleration, relate to previous research in the area and how this work contributes to the field of physics education research.

7.4 Discussion of variations in conceptions of acceleration

The range of variation in the qualitatively different ways that these students perceived acceleration was a surprising result within this study. Although numerous studies have found that students do not perceive acceleration in the same way as an expert (Trowbridge & McDermott, 1981; Reif & Allen, 1992; Smith *et al.* 1993), it was the dimensions of variation that were interesting. Often an individual student's perception of acceleration could be described by a number of the categories, depending on the context in which acceleration was being discussed. Again this proves that learning is contextual.

This does not appear to concur with the contention that students have stable misconceptions when it comes to acceleration (Caramazza *et al.* 1981). However, it would appear to agree with the concept of resources which may be activated in certain contexts (Hammer, 2000; Redish, 2004; Sabella & Redish, 2007). Whichever model of cognitive knowledge structure one may deem appropriate, each individual student is aware of the concept of acceleration in their own way and their understanding of acceleration is a result of the critical features which they have discerned during their previous experiences of acceleration. Whether or not their understanding depends on the context in which acceleration is discussed depends on whether they have learned to perceive acceleration in a powerful way. These categories represent a description of the variation in acceleration as perceived by these students.

Reif & Allen (1992, pg 9) suggest that interpreting a scientific concept, such as acceleration, "requires the availability in memory of pertinent knowledge about this

concept; some of this knowledge then needs to be retrieved and applied in any particular instance". Marton & Booth (1997, pg 143) suggest that each learning situation, in which something learned is to be applied, has a relevance structure and they define relevance structure as "the person's experience of what the situation calls for, what it demands. It is a sense of aim, of direction, in relation to which different aspects of the situation appear more or less relevant." In order for that knowledge to be present in memory and be applied in a particular instance it must be called for by an appropriate relevance structure. Therefore if the relevance structure of the situation, or the concept as the case is here, is expansive then the concept may be understood in a variety of contexts. This is proposed within category 6's perception of acceleration. The questions used in the interview (Interview set B) which were designed to probe students' perception of acceleration required students to discuss acceleration in different contexts; acceleration due to gravity, vertical acceleration, acceleration in the horizontal direction and during the interview students were also faced with the acceleration within a quantitative context. Therefore it was possible to observe how the relevance structure of certain situations varied for certain students. For instance, some students applied correct knowledge of acceleration when discussing acceleration in the horizontal direction while not discerning that the same knowledge was applicable for acceleration in the vertical direction.

Variations in students' understanding of acceleration have previously been explored (Dall'Alba *et al.*, 1993) and categories describing these variations have been constituted from data obtained through analysis of interview transcripts. These categories were constituted from the data obtained from one qualitative problem asking students to discuss the acceleration of a ball which is thrown into the air and follows a projectile trajectory (as

described in Chapter 2). Therefore these categories describe the variations in understanding of acceleration within this one context. The six categories of description discovered by Dall'Alba *et al.* (1993) are: Caused by gravity, rate of change of velocity; rate of change of velocity; gravity is closely linked but not causally; acts as a force; differences in velocity; forces – acceleration due to gravity and acceleration of the ball. The 'caused by gravity, rate of change of velocity' category represents the highest level of understanding due to the fact that acceleration is seen as the rate of change of velocity and that there is a causal relationship between acceleration and the force of gravity. Similarly the perception of acceleration category 6, presented here, is regarded as describing the highest level of understanding for the same reasons. There are other similarities between the two sets of categories, for example the 'acts as a force' category has a close connection to perception of acceleration category 4 but, because the categories presented here were constituted from a range of contexts in which acceleration was discussed, there are also major differences. One such difference is that Dall'Alba *et al.* (1993, pg 631) found that expressions about positive and negative acceleration were not critical features of the students' understanding and "were not attributable to specific conceptions". I, on the other hand, discovered that this was a critical feature which illustrated a variation in the perception of acceleration and this is shown in the distinction between categories 5 and 6.

7.5 Chapter summary

The categories describing the variations in perceptions of acceleration presented here provide a detailed explanation of how acceleration is understood by a set of introductory physics students. This was achieved through the analysis of interviews which were aimed at exploring students' conceptions of acceleration in a number of different contexts. The variations again highlight the necessity for instruction to emphasise the importance of a qualitative understanding, in this case, of acceleration, velocity and force.

CHAPTER 8

CONCLUSIONS AND IMPLICATIONS

8.1 Introduction

This research set out to investigate the variations in introductory physics students' problem solving approaches and their conceptual awareness within the context of the Irish higher education system. This research studied the initial knowledge state of a large number of students entering the higher education system in Ireland through the use of a research-based diagnostic tool and subsequently employed the same tool to explore the development of conceptual understanding after formal instruction in one area of physics, i.e. mechanics. Using the phenomenographic assumptions and methodology the variations in the participating students' approaches to problem solving and conceptual awareness were discovered, along with a description of the variations in perceptions of a key physics concept. Furthermore, it explored the relationships between conceptual awareness and approaches to problem solving. The main findings and implications from this study are summarised below, followed by the final concluding remarks.

8.2 Summary of findings

The findings from this study revealed that the majority of students beginning to study science at third level in Ireland have very limited understanding of mechanics concepts as measured by the Force and Motion Conceptual Evaluation. This is also true for those students who have studied physics in school, even at a higher level and achieved high grades. This implies that the Irish high school education system has no effect on students' conceptual knowledge of physics. Furthermore the exit examination, the Leaving Certificate, appears not to assess conceptual understanding. Findings revealed that after formal instruction in mechanics only a small number of students had begun to develop an understanding of the concepts which were evaluated by the FMCE. Traditional instruction, where the goal is to transmit knowledge to the students in the form of well defined learning outcomes, had little to no effect on the students understanding of the concepts involved. However, it is the small number of students who did exhibit a gain in understanding who are interesting. The only students who seemed to improve in their ability to correctly answer questions on the conceptual nature of mechanics were those who had learned through problem based learning. This is an important finding and one which has not been presented previously in the literature; that problem based learning has a positive effect on students' conceptual understanding as measured by a reliable research-based diagnostic tool.

Findings from this study revealed that within two cohorts of introductory physics students there were a limited number of qualitatively different ways in which they approached

problem solving. It was found that those qualitatively different ways could be discovered in both cohorts, indicating that the descriptions of the variations in approach to problem solving may be generalisable across different cohorts of novice problem solvers. The categories describing the variations in approach to problem solving represent the problem solving state of a set of novice physics students. Although none of the students could be described as experts, the findings reveal that within the category of novice there are critical variations which allow for a better description of the problem solving approaches of a set of students.

The research findings also provided a qualitative description of the conceptual awareness of the same set of novice physics students and constituted the variations within conceptual awareness for those cohorts. These categories may represent stages of conceptual knowledge development but this could only be proven through the use of a longitudinal study by examining students' knowledge as they progressed through their undergraduate careers. This is a feature of the research presented here which will be included in future work in this area. However, the categories presented here which describe the variations in conceptual awareness do highlight the expanding awareness of the significance of the conceptual nature of physics. Through this expanding awareness there is an expanding level of understanding of the specific concepts involved in the situations, how they are related to each other and how they are related to the whole situation.

By examining the relationship between conceptual awareness and approach to problem solving the findings revealed that in order for students to become adept problem solvers it

appears that it is first necessary for them to be aware of the conceptual nature of physics. As an awareness of the conceptual nature of physics incorporates an expanding level of understanding of the specific concepts and how they are related to each other, it is more likely that through this awareness students will have the capability to simultaneously discern the critical features of a problem situation and approach the problem in a powerful manner.

The final finding from this research study was a detailed description of how a set of introductory physics students understood the concept of acceleration. This level of detail into the variations in conceptions of acceleration has not previously been presented in the literature. The findings demonstrated that for the most part understanding of acceleration was highly contextual and that in order for students to develop a deep understanding of acceleration instruction must emphasise a qualitative understanding of the concept. This finding more than any other presented here emphasises that repetitive problem solving alone does not develop in students a powerful understanding of specific concepts.

8.3 Implications and recommendations

8.3.1 Implications for students

The implications that the findings from this research have for students are numerous. The categories describing the critical variations in approaches to problem solving could allow students to be explicitly aware of the differences in approaches they employ when solving problems. For students these categories could highlight the need for a qualitative structured strategy when faced with a complex problem and perhaps the sufficient condition of a plug-and-chug approach when a simple algorithmic problem is encountered. Awareness of the variations in approaches should also encourage development of problem solving skills by highlighting for students the limitations of their approaches and encouraging them to be more reflective in the problem-solving process. The same is true if students were aware of the variations in conceptual awareness, although when viewed together these categories represent more of a development from limited conceptual awareness to a more complete conceptual awareness. However, allowing students to consider the potential limitations of their conceptual awareness is an important step in the development towards a more complete conceptual knowledge. In short, an awareness among students of these categories and their limitations may encourage metacognition in the learning process.

The categories describing the variations in conceptions of acceleration, having been constituted from discussions of acceleration in a number of contexts, represent the critically

different ways in which acceleration is understood. Therefore an awareness of these may help students develop a more complete understanding of the concept.

8.3.2 Implications for lecturers

The findings from this research also have important implications for lecturers. If lecturers are aware of the variations in their students' knowledge and approaches they can encourage the development of more complete awareness and effective problem-solving approaches through the use of appropriate learning activities. More specifically, if lecturers are aware of the qualitatively different ways in which students approach problems they will be more likely to identify those approaches which their students are adopting and begin to set tasks that highlight the limitations of these approaches. For instance, when developing assessments or examinations they could include a range of problems/questions which identify and examine different problem solving abilities and approaches. The variations in conceptual awareness should highlight for lecturers the need to emphasise to their students the conceptual nature of physics and through this help the students to develop as problem solvers.

8.3.3 Implications for curriculum design

The implications that the findings from this research have for curriculum design are another important aspect of this research. The categories describing the variations in approaches to problem solving, students' conceptual awareness and the relationship between them allow for constructive alignment (Biggs, 1999) within the design of the curriculum. That is, the learning activities and the assessment could be aligned with the learning outcomes of the curriculum. Therefore the learning activities and assessments could be developed to include problems which explicitly highlight weaknesses in approaches or indeed in conceptual knowledge. For example within a problem based learning course a range of problems could be designed in order to demonstrate and examine the students' approach to problem solving on particular problems. Tutor questions could be developed which aid the tutor in understanding the students' knowledge at that moment in time, therefore helping the tutor to encourage the student towards a more powerful way of seeing.

8.3.4 Implications for DIT School of Physics

This research has already had an impact on the curriculum design and teaching and assessment practices within the School of Physics in DIT. The practices of the problem based learning tutors have been informed by the categories describing the students' approaches to problem solving, variations in conceptual awareness and variations in

conceptions of acceleration. One example of this is that tutors will now ask numerous questions of the students to determine if the basic concepts are in fact understood, in all contexts. There have been changes to problems within the courses to reflect the need for an emphasis on both qualitative and quantitative knowledge of the physics involved and to encourage students to discern the critical aspects in these novel situations.

In terms of the conceptual awareness, the tutors, through subsequent research studies, are now developing Socratic questions and other strategies, such as tutorials and assessments, to help the students move from the lower categories to the higher categories. In terms of problem-solving approaches, a range of problems, or parts of problems, are now used to identify, and highlight the limitations of, different problem-solving approaches.

Another positive outcome of this research is that the level 7 problem based learning course has been evaluated and cemented as a viable and improved alternative to the traditional lecture based method of delivery. Examination questions have been developed for both the level 7 and level 8 problem based learning courses which have been aligned with the learning activities and learning outcomes and this remains an iterative process as the research continues.

8.4 Limitations of the study

As with all research studies there were limitations involved in this physics education research, although at all times I endeavoured to be aware of these limitations in an effort to minimise their effect on the research outcomes.

There were limitations involved with the use of the research-based diagnostic tool, the Force and Motion Conceptual Evaluation, as it is was used to conduct a quantitative evaluation of an essentially qualitative phenomenon – conceptual understanding. Another limitation of the use of the FMCE within the Irish context is that it was developed in the US as an evaluation of introductory physics students in the US. However, this limitation is minimised by the fact that the FMCE was employed mainly as a tool with which to set the context of the study and to provide a comparison of the participating students' conceptual knowledge “as measured by the FMCE”.

Another limitation which I was aware of while conducting this research was that the research study might have been designed differently and therefore the research findings might also have been different. By this I mean that if I had chosen an alternative methodology, such as phenomenology, with which to conduct the research the outcomes may not have been the same. However, the methodology employed in this study was deeply grounded in the theoretical assumptions that I brought to the research and which are fully justified and explained in Chapter 3. Included in the area of research design is the limitation of having a limited number of research participants.

Yet another limitation comes from the context of the research setting; the research was carried out in one institution in one country. However, readers can draw parallels to their own learning and teaching situation.

8.5 Further Work

In many ways this research study has probably raised as many questions as it has answered and it was difficult to prevent the research from losing focus, as many interesting issues arose during the course of the study which could not be fully addressed due to lack of time. These issues have important implications for physics education and would benefit from further research, such as:

- It is suggested here that problem based learning improved student learning in mechanics, but the reasons have not yet been fully investigated. Ongoing further work involves an investigation of what aspects of problem based learning help students develop understanding.
- Within the group there is also ongoing work which is investigating the qualitatively different ways in which students participate in problem based learning in an effort to discover why some students learn more effectively than others in pbl.
- Further work is being already being carried out which aims to discover the relationship between the students' perception of the learning environment, their approaches to problem solving and their conceptual awareness (see Appendix F).
- It is a recommendation of this research that educators should help students develop as problem solvers and therefore further work would involve an examination of strategies to encourage this development.

8.6 Concluding remarks

The objective of this thesis was to provide an overall description of the problem solving and conceptual awareness state of a sample set of Irish introductory physics students in the context of mechanics by employing the phenomenographic assumptions and methodology outlined in Chapter 3. This description has been achieved by constituting categories which describe the variations in approaches to problem solving and variations in conceptual awareness, including a description of the variations in perceptions of a specific concept in mechanics.

One of the most important outcomes of this study has been the processes which were used to achieve the aims of the research. The theoretical assumptions which underpin phenomenography as a methodology and variation theory as a theory of learning have become integral to the development of the Physics Education Research Group in DIT.

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APPENDIX A: Leaving Certificate Grades

TABLE OF LEAVING CERTIFICATE GRADES

Table A: Table of Leaving Certificate grades and corresponding CAO points awarded

Percentage Range	Grade	Points for Higher	Points for Ordinary
90 – 100	A1	100	60
85 – 89.9	A2	90	50
80 – 84.9	B1	85	45
75 – 79.9	B2	80	40
70 – 74.9	B3	75	35
65 – 69.9	C1	70	30
60 – 64.9	C2	65	25
55 – 59.9	C3	60	20
50 – 54.9	D1	55	15
45 – 49.9	D2	50	10
40 – 44.9	D3	45	5
25 – 39.9	E	0	0
10 – 24.9	F	0	0
0 – 9.9	NG	0	0

APPENDIX B: Sample Problem Based Learning Problems

APPENDIX B1 – Sample mechanics problem

California Train Crash

Your group have been asked to take over an emergency situation at the California Train Control Centre. As none of the staff there have any special training, there will be a terrible accident with high casualties unless you can find a solution to their problem. On entering the Centre you are informed of the following:

There is a passenger train on the track which has a serious engine fault. The train has eight carriages with 200 passengers. The driver cannot control the speed so it is travelling at a constant velocity of 30 ms^{-1} in a north-east direction. This train has only 9 km of track left. You can communicate with the driver but he has no control over the engine.

However there is another engine (engine only) on the same track 600 metres behind the uncontrolled train. You can communicate with this driver and he has complete control over the engine. You can assume that the 600 metres is the distance from the front of one train to the back of the other. The track between the trains is straight as is the remaining 9 km.

At the moment the two trains are travelling at the same speed.

An engineer in the Centre informs you that if the train behind were to catch up to train ahead the trains can be remotely connected together. The leading engine can then be switched off. Then the train behind can be used to stop the other train. However the connection has to be made when both trains are travelling at the same speed.

Remember time is running out.

After the accident has been avoided your team must fill in the attached **Form 11A**.

APPENDIX B2 – Sample mechanics problem

NukeWaste Inc 'For a Brighter Environment'

Your group works for NukeWaste Inc the US's leader in nuclear waste management. One of your trains transporting high level nuclear waste has gone out of control and may be headed for a collision. It looks like your train will collide with a passenger train at a junction in a large town (population 20,000).

The president of the company is a bit unscrupulous and is concerned about the public image of the company. They have already lost two court cases for poor safety procedures and he doesn't want to be in the press again. He wants to know if the trains will actually crash, if not then he won't evacuate the town and he will hush up the story.

Your group have been asked to determine if there will be a crash. As none of the Amtrak staff there have any special training, they are uncertain if there is to be a terrible accident with high casualties. On entering the Amtrak Control Centre you are informed of the following:

There are two trains, on which the drivers have lost full control of the engines and the two trains may collide at a cross junction.

There is a passenger train (Train A) West of the cross junction travelling due East on the track and has a serious engine fault. The driver cannot control the velocity of the train and you he informs you of the following:

- It is currently travelling at a velocity of 20 ms^{-1} .
- It is 7000 (7 km) metres from the junction
- It is accelerating at 0.1 ms^{-2}
- The speed of the train will only stop increasing when it reaches it maximum speed of 115 kph (kilometres per hour)
- The length of the train is 150 m

The Nuclear Waste Train (Train B) is on the other track North of the cross junction and travelling due South. The driver cannot control the velocity of the train and informs you of the following:

- It is currently travelling at a constant velocity of 25 ms^{-1} .
- It is 6000 (6 km) metres from the junction
- At present, he is unable to speed up or slow down, i.e. he cannot accelerate
- The length of the train is 150 m

Will the trains collide? Should they evacuate the town?

APPENDIX C: Interview Protocols

APPENDIX C1: Interview set A protocol

Problem solving questions

The interviewer first explains to the student that she would like the student to begin by expressing their first thought on the problem, then stating what they thought the problem involved, how they believed they would go about solving the problem and finally to actually solve it while talking aloud as they proceeded.

The interviewer then read the problem aloud and allowed the student time to read the problem.

1. If I dropped a 2 kg watermelon from the top of a three-story building, say around 10 m high, how fast will the watermelon be going when it hits the ground?

What does this problem involve?

I'd like you to describe how you will go about answering this problem.

Now talk me through each action that you take in answering the problem.

(What are you unsure about?)

Are you confident about the solution?

2. Say you are standing here, holding out your hand, which is about 2 m above the ground, and you throw a ball straight up. If the ball leaves your hand with a speed of 15 m/s, how long will the ball be in the air before it hits the ground?

What does this problem involve?

I'd like you to describe how you will go about answering this problem.

Now talk through each action that you take in answering the problem.

(What are you unsure about?)

Are you confident about the solution?

3. Just for the fun of it, you and a friend decide to enter the famous Tour de France bicycle race. You are riding along at a comfortable speed of 10 m/s when you see in

your mirror that your friend is going to pass you at what you estimate to be a constant 15 m/s. You will, of course, take up the challenge and accelerate just as she passes you until you pass her. If you accelerate at a constant 0.25 meters per second each second until you pass her, how long will she be ahead of you?

What are your first thoughts on this problem?

How will you go about answering this problem?

Now talk through each action that you take in answering the problem.

(What are you unsure about?)

Are you confident about the solution?

4. A car with a mass of 1300 kg is initially moving at a speed of 40 m/s when the brakes are applied and the car is brought to a stop in 15 m. Assuming that the force that stops the car is constant, find,
- The magnitude of that force, and
 - The time required for the change in speed.

What are your first thoughts on this problem?

How will you go about answering this problem?

Now talk through each action that you take in answering the problem.

(What are you unsure about?)

Are you confident about the solution?

5. You have been hired to design the interior of a special executive express elevator for a new office building. This elevator has all the latest safety features and will stop with an acceleration of $g/3$ in case of any emergency. The management would like a decorative lamp hanging from the unusually high ceiling of the elevator. You design

a lamp that has three sections, which hang one directly below the other. Each section is attached to the previous one by a single thin wire, which also carries the electric current. The lamp is also attached to the ceiling by a single wire. Each section of the lamp weighs 7.0 N. Because the idea is to make each section appear that it is floating on air without support, you want to use the thinnest wire possible. Unfortunately the thinner the wire, the weaker it is. To determine the thinnest wire that can be used for each stage of the lamp, calculate the force on each wire in case of an emergency stop.

What are your first thoughts on this problem?

How will you go about answering this problem?

Now talk through each action that you take in answering the problem.

(What are you unsure about?)

Are you confident about the solution?

6. Two blocks, one with a mass of 1 kg the other with a mass of 2 kg, start from rest. They each experience a constant force of 10 N for 1 s. What are their kinetic energies after the force has been applied.

What are your first thoughts on this problem?

How will you go about answering this problem?

Now talk through each action that you take in answering the problem.

(What are you unsure about?)

Are you confident about the solution?

APPENDIX C2: Interview set B problem

Just for the fun of it, you and a friend decide to enter the famous Tour de France bicycle race. You start the race and accelerate at a rate of 0.25 meters per second each second until you reach the 50 m mark. At this point you notice that your friend had to incur a time delay and wasn't allowed to start the race for a full minute after everyone else, so you stop accelerating. When your friend does begin she also accelerates at 0.25 meters per second each second for 40 seconds and then maintains a constant speed. You are riding along at your comfortable speed when you see in your mirror that your friend is going to pass you. You will, of course, take up the challenge and accelerate just as she passes you until you pass her. If you accelerate at a constant 0.25 meters per second each second until you pass her, how long will she be ahead of you?

APPENDIX D: Force and Motion Conceptual Evaluation Results

APPENDIX D1

Figures D1a and D1b below are histograms illustrating the overall mean pre- and post-FMCE percentage scores and the percentage normalised gain for the level 8 students from years 2 and 3 of this study respectively.

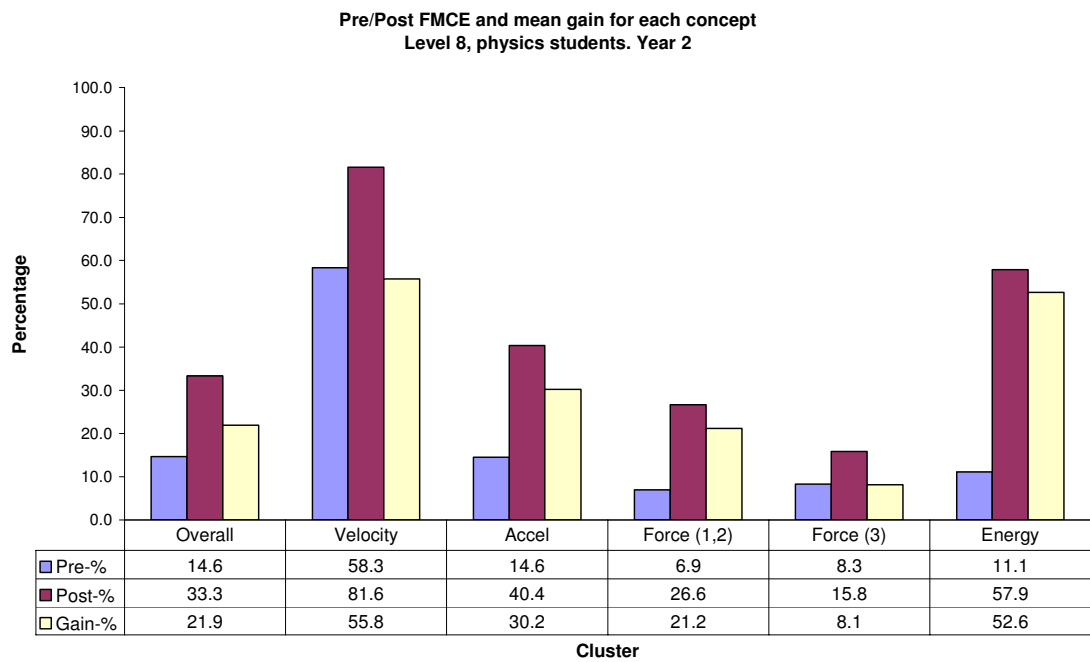


Figure D1a: Bar Chart of FMCE scores for level 8 students, year 2 of the study

Pre/Post FMCE and mean gain for each concept
Level 8, physics students. Year 3

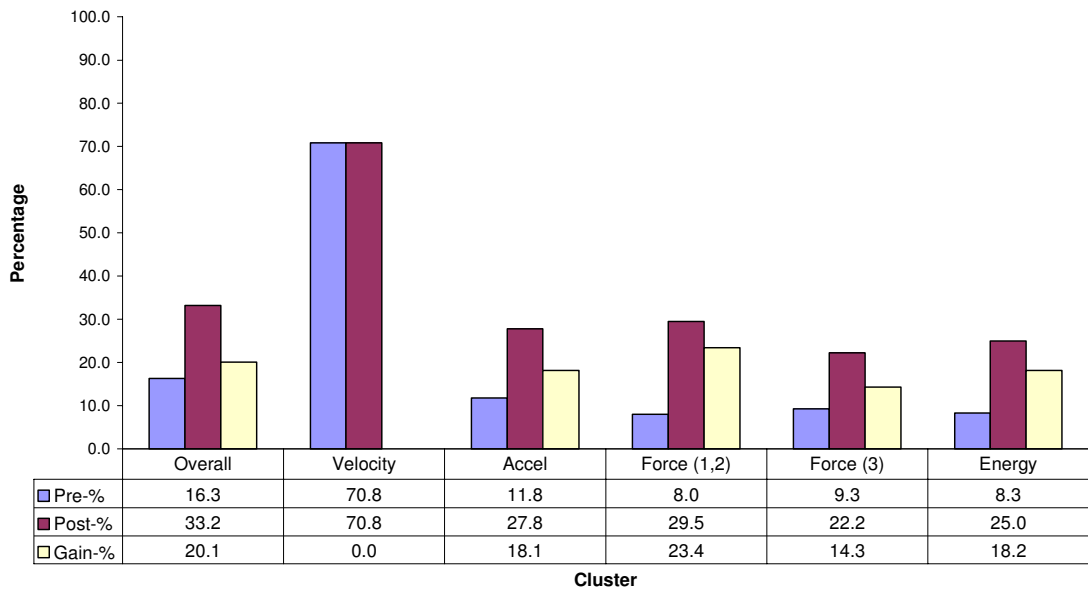


Figure D1b: Bar Chart of FMCE scores for level 8 students, year 3 of the study

APPENDIX D2

Figures D2a and D2b below are histograms illustrating the overall mean pre- and post-FMCE percentage scores and the percentage normalised gain for the students who entered college to study a primary degree other than physics from years 2 and 3 of this study respectively.

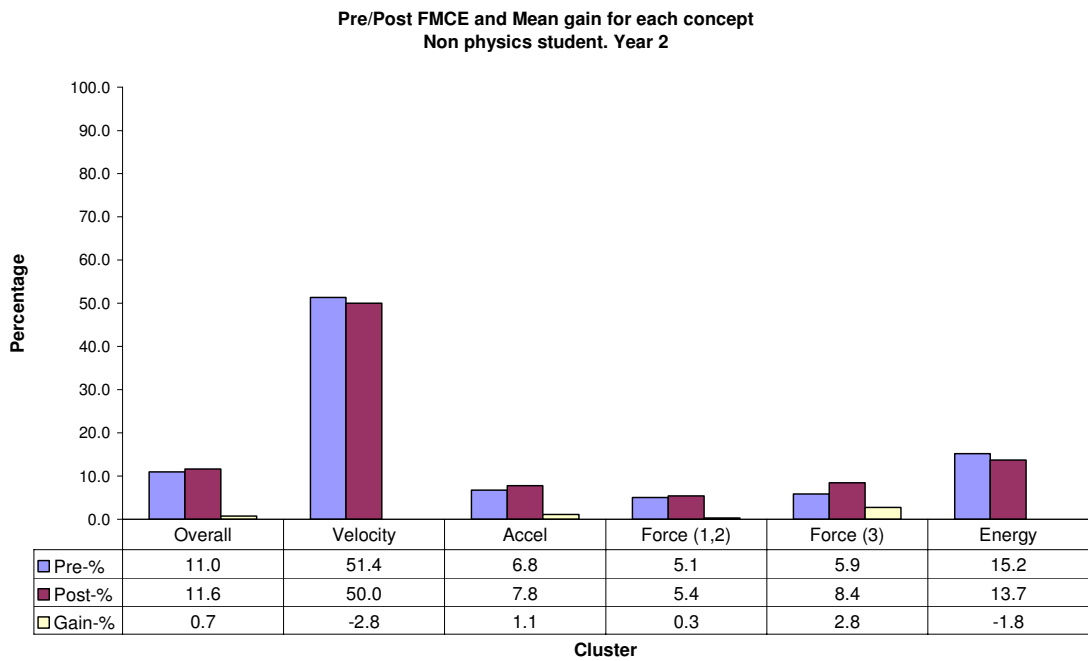


Figure D2a: Bar Chart of FMCE scores for non-physics students, year 2 of the study

Pre/Post FMCE and mean gain for each concept
Non-physics students. Year 3

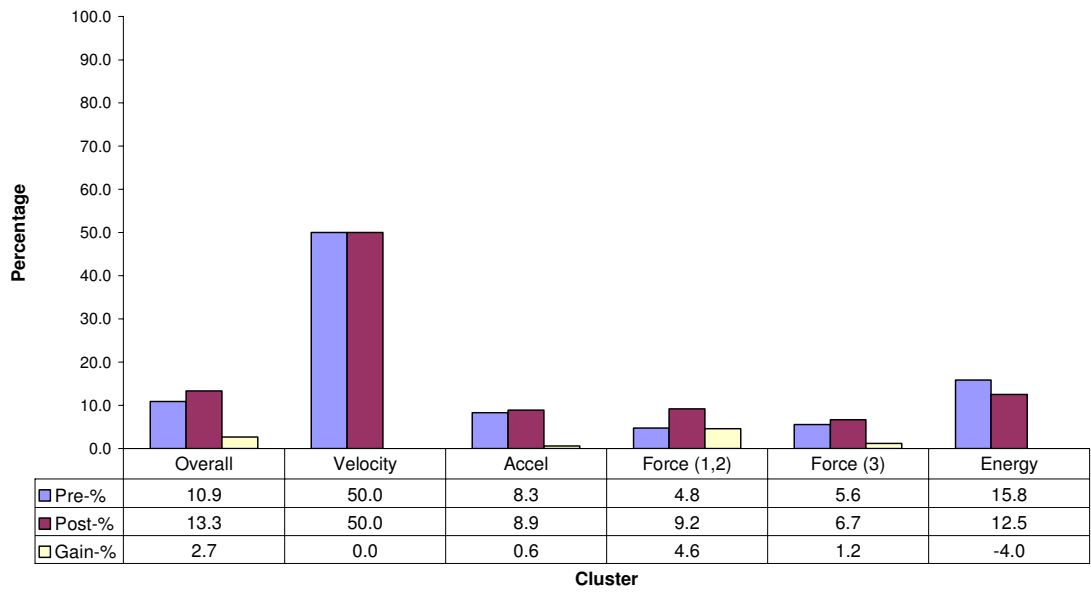


Figure D2b: Bar Chart of FMCE scores for non-physics students, year 3 of the study

APPENDIX D3

Figure D3 below is a histogram illustrating the overall mean pre- and post- FMCE percentage scores and the percentage normalised gain for the level 7, general science, students from year 3 of this study, during which the pedagogical delivery of the physics material was through problem based learning.

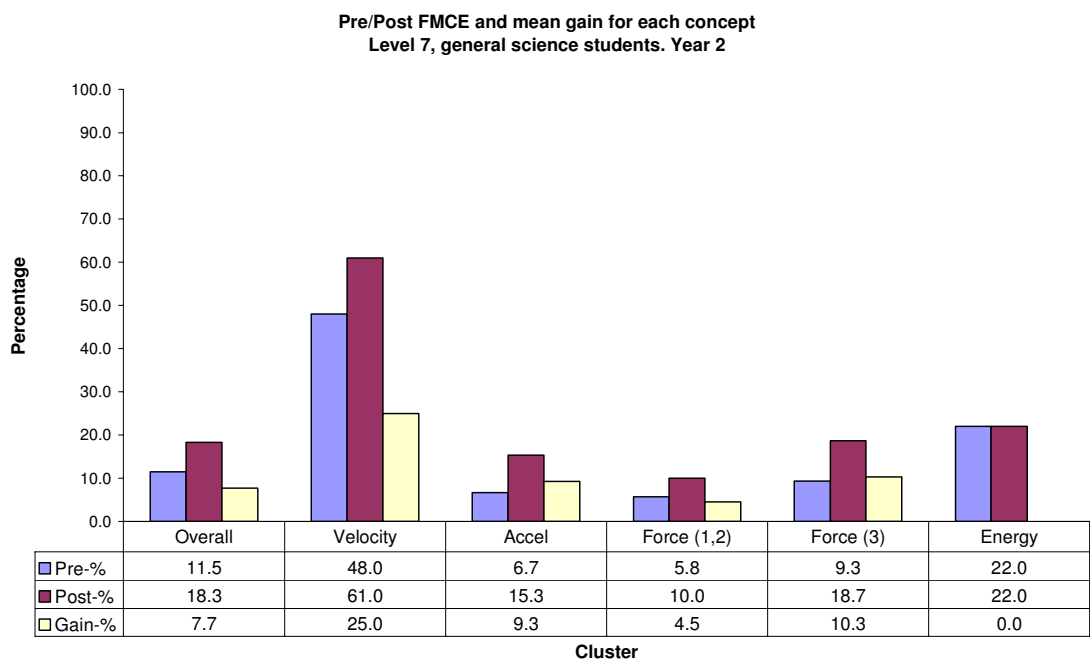


Figure D3: Bar Chart of FMCE scores for general science students, year 3 of the study

APPENDIX E: Interview Participant Profiles

Table E1: Profiles of the twenty-two interview set A participants

Student age	Previous physics	Degree choice	Pre-FMCE score	Post-FMCE score
21	Honours	general Science	9.10	9.10
21	No physics	general Science	9.10	12.10
19	No physics	general Science	6.10	12.10
19	No physics	general Science	0.00	9.10
19	No physics	general Science	18.20	12.10
18	Fail (honours)	general Science	36.40	15.20
18	No physics	general Science	15.20	12.10
18	Ordinary	general Science	9.10	6.10
20	No physics	general Science	15.20	9.10
18	No physics	forensic analysis	6.10	9.10
19	No physics	forensic analysis	15.20	18.20
19	Honours	forensic analysis	9.10	12.10
18	Honours	clinical measurement	6.10	12.10
18	No physics	clinical measurement	3.00	3.00
18	Honours	physics technology	12.10	24.20
18	Honours	physics technology	81.80	78.80
18	Honours	physics technology	9.10	6.10
19	Honours	physics technology	63.60	90.90
24	No physics	physics technology	33.30	72.70
19	Honours	medical physics	15.20	69.70
19	Honours	medical physics	24.20	63.60
18	No physics	medical physics	18.20	15.20

Table E2: Profiles of the twenty interview set B participants – entire interview

Student age	Previous physics	Degree choice	Pre-FMCE score	Post-FMCE score
19	No physics	General science	9.10	15.20
19	No physics	General science	3.00	39.40
19	No physics	General science	12.10	18.20
19	No physics	General science	0.00	12.10
20	No physics	General science	15.20	27.30
18	No Physics	General science	21.20	15.20
18	Honours	General science	12.10	36.40
24	Ordinary	General science	15.20	36.40
19	Honours	Medical physics	---	78.80
18	Honours	Medical physics	33.30	42.40
20	Honours	Medical physics	15.20	42.40
18	No physics	Medical physics	6.10	42.40
18	Honours	Medical physics	---	6.10
23	Ordinary	Medical physics	18.20	81.80
19	No physics	Medical physics	12.10	18.20
19	Honours	Medical physics	18.20	39.40
18	Honours	Medical physics	12.10	---
26	Ordinary	Nanotechnology	27.30	63.60
20	Honours	Physics technology	18.20	15.20
19	Honours	Physics technology	12.10	6.10

APPENDIX F: Perceptions of the Learning environment

PERCEPTIONS OF THE LEARNING ENVIRONMENT

The perceptions phase of Interview set B was designed to elucidate the variations in the ways that students perceived their learning environment, and as the cohort was diverse the learning environment itself varied and this is discussed in section 3.6 of the thesis. By perception of the learning environment I mean perceptions of how their physics modules are presented to them and what is expected from them in their study of physics. I assumed that there would be a limited number of qualitatively different ways in which these students would perceive their learning environment. Perceptions were investigated by asking a number of open ended questions which were prepared prior to the interview and subsequently following any further lines of reasoning during the interview. The prepared questions used are presented below:

1. Did you study physics/science in school?
2. Was it a subject that you enjoyed? Tell me why/ why not?
3. Is there a difference between how you learned physics in school and how you learn physics here?
4. Thinking about studying physics now (in DIT), in your opinion what is the most important element of studying physics?
5. In your opinion what is the most important element for passing when studying physics?
6. What do you think your lecturer would count as most important element of studying physics?
7. Describe how you view the role of your lecturer in physics.

8. Describe what you think SHOULD be the role of the lecturer.
9. How do other members of your class affect your learning, if at all?
10. Is there any way, in your opinion, that your physics course could be improved?
11. Finally do you enjoy studying physics now?

Students' perceptions of their learning environment

From analysis of the data from the interview transcripts five distinct categories emerged that described the variations in these students' perceptions of their learning environment, specifically students' perception of what was expected from them during the course of their study in introductory physics. As described previously (section 3.5.4) and above the students who participated were enrolled in six different programmes, four of these were delivered through problem based learning and two were traditionally lecture based. The categories are all internally related and are described using two components; how the environment is described and what is focused upon. Below each category is described in some detail with examples from the interview transcripts chosen to support the categories.

Table F1: Profiles of the eight interview set B participants – perceptions section only

Student age	Previous physics	Degree choice	Pre – FMCE	Post - FMCE
18	No physics	Clinical measurement	9.10	18.20
19	No physics	Clinical measurement	9.10	18.20
21	No physics	Clinical measurement	12.10	27.30
18	No physics	Clinical measurement	6.10	12.10
20	No physics	Clinical measurement	12.10	15.20
19	No physics	Forensic analysis	3.00	9.10
19	Honours	Forensic analysis	30.30	---
19	No physics	Forensic analysis	9.10	12.10

Learn equations

The emphasis of this category describing the perception of the learning environment is the importance of knowing all of the equations that are presented within the physics course. This importance is based on the mathematical nature of physics and therefore success in the course depends on the ability to reproduce and use these equations. The role is the lecturer is to provide the information that is needed to be successful in the course.

The following excerpt is from a section of a transcript in which a student is discussing how she approaches studying for a physics exam:

Student: *Like, I'd just write out all the formulas that I need to know on a piece of paper, then learn the formulas off and then later see where I can use these formulas like.*

Later in this interview the interviewer asks the student to describe how she views the role of the lecturer in physics, she replies:

Student: *Basically to teach us, make sure we understand it.*
Interviewer: *How do they do that?*
Student: *Em, by giving us examples and some questions like.*
(Transcript 45)

Another example of this category is illustrated in the extract below; again this student is discussing her approach to studying for exams:

Student: *That's what I mostly focused on [equations], I did a bit of theory as well but I felt that the equations were more important to learn than the theory. Probably get me more marks as well!*
(Transcript I)

Learn theory and definitions

Within this category there is evidence that being present and listening in the lectures is very important, however in order to pass exams it is necessary to rote learn lecture notes and theory. Within this perception, as in the perception above, the role of the lecturer is to provide the information that is needed to be successful in the course.

The following is an excerpt from a transcript in which the student has been asked what they believe is the most important element of studying physics, the student replies:

Student: *I think just kind of listening to it when it is first said to you and then picturing it in your head really, trying to understand it that way.*
Interviewer: *Right, and so what in your opinion would be the most important element for passing when you're studying physics?*

Student: *I think learning, just learn it off*
Interviewer: *Right*
Student: *I know I did that for the Christmas exams, I just had to learn a lot of it just off, whether I kind of understood it or not, I just learned it off.*
Interviewer: *Right, and did you find that got you through?*
Student: *Yeah it did, I passed so it worked.*

(Transcript 44)

Practice

Within this category there is also evidence that being present and listening in lectures is very important in order to understand the material, and this importance is based on the requirement of being able to use the information obtained in lectures and tutorials to practice problems. Within this category the lecturer is paramount as he/she provides the information and examples that are necessary to be successful in the course.

An illustration of this perception is shown below; in this the student has just been asked what she believes is the most important element of studying physics:

Student: *Just making sure you understand, like if you go out the door and you don't understand it, when you go to do it by yourself you're not going to. So just use the tutorials to the best of your advantage because it makes such a difference when you ask something you don't really understand.*

Later in the interview as the student is discussing studying for an exam, she says:

Student: *Doing out problems, like practicing, actually writing the stuff out. That's what I did because it's really hard to learn because there are so much different rules and stuff. It's easier if you just write them out and do the problems cos it's easier that way.*

(Transcript K)

Overall view of everything

The focus of this category is on the importance of having a general feel for everything that is encountered within the physics course, rather than on specifically understanding the concepts. This importance is based on the requirement for interaction between the students and the lecturers. Within this category students are responsible for their own learning although the aide of their lecturers and classmates is paramount in being successful in the course.

An example of this category is taken illustrated below; this student has just been discussing learning physics in secondary school – in a negative light. The interviewer asks:

Interviewer: *Ok, whereas now?*

Student: *There is so much interaction with the teachers, it's brilliant. With physics like, because you can actually sit and talk and you get the time. Where there is only a small group of us to be able to say 'Oh god, where are we?'*

When this student is asked what she believed her lecturers would count as the most important element for studying physics, she replies:

Student: *Em, the actual class, like being there and doing everything and trying to explain. And trying to get us to do it as well by ourselves.*

(Transcript 24)

A further illustration of this category is shown in the extract below, the student has just been asked what she believes is the important element for passing her physics course:

Student: *Well if you're doing questions, to be able to say exactly how you've done the question, using what formulas, how exactly you did it. Whereas in the leaving [Certificate] you just learned the stuff off and you'd be fine.*

(Transcript 39)

Understand

This category is similar to the one above, however within this category of the perception of the learning environment it is of primary importance to understand the concepts and theory related to the physics course. The importance of this is based on the requirement of being able to use and link this knowledge in a variety of situations. Also, within this category there is evidence that learning is the responsibility of the student; the role of the lecturer is as a guide and devil's advocate. Success in the course will be an eventuality.

For instance when asked what he believed was most important about studying physics with his programme, one student replied:

Student: *The problem based learning is really important, you learn an awful lot without having to study, you know without having to learn a load of stuff off. If you understand the concepts, that's definitely useful. A lot more work but you end up learning more, understanding more anyway.*

The student then goes on to compare studying physics in secondary school to studying in college:

Student: *A lot of the stuff in secondary school physics, you learn equations but relating one to the next, relating the concepts or linking them together didn't really come naturally, so it's easier this way.*
(Transcript 32)

Another illustration of this perception is shown below as this student discusses what she believes is the most important element of studying physics:

Student: *I think understanding, and eh not the equations but the things that cause things to happen like this. Its understanding, I think equations go later.*

Later in the interview this student responds to the question about what she believes her lecturers would count as the most important element:

Student: *I think understanding and being able to explain it. If we can understand it, then explain it.*

(Transcript 34)

Variation in perception of the learning environment

Relations between the categories of description

Studies have shown that students' epistemological beliefs about the nature of physics and their expectations of studying physics have an effect on how they approach physics and their learning of physics (Hammer, 1994; 2000; Lising & Elby, 2005; May & Etkina, 2002; Redish *et al.*, 1998; Roth & Roychoudhury; 1994). The majority of these studies explore the correlations between learning outcomes and specific sets of epistemological beliefs and some produce a taxonomy of these epistemological beliefs; these studies have been outlined in Chapter 2. Hammer (2000) describes epistemological resources, which are at a finer grain size than beliefs and like conceptual resources these epistemological resources can be activated in certain contexts. Marton and Booth (1997) discuss the relevance structure of a learning situation, indicating that the way in which an individual experiences a situation as a whole will determine that individual's perspective of the component parts. In the context

of this research therefore I felt that it was necessary to explore the variation in the students' perception of what was required of them within their learning environment.

Table F2: Key aspects in the range of variation in perception of the learning environment

Themes of expanding awareness	Categories				
	Learn equations	Learn theory and definitions	Practice	Overall view of everything	Understand
Importance lies in	Learning equations	Learning lecture notes	Practicing problems	Learning physics	Understanding concepts and theory
Develop capability to	Reproduce equations in exams	Reproduce lecture material	Answer/solve problems	Link information through interactions with classmates, material and lecturer	Link and use knowledge
Role of lecturer	Present information	Present information	Example setter	Arbitrator	Guide

The categories describing the variations in perception of the learning environment presented above are based on the empirical evidence from the transcripts. I will now present the logical evidence for the hierarchical structure of these categories based on the themes of expanding awareness which emerged through analysis of the data. In Table 5.4

the themes of expanding awareness are shown along with the critical aspects of each category which serve to highlight the inclusive structure of the categories.

Within the learn equations category the focus, as the name suggests, is on learning the equations which have been presented in physics class and being able to reproduce these equations in order to pass exams. There appears to be little or no awareness of the conceptual nature of physics or of the requirement to understand these concepts. Within the learn theory and definitions category the focus is again on rote learning the information that the lecturer has presented in order to pass exams. There is awareness that there is more to learning physics, however the learning environment simply requires that the material is 'known'. Within the practice category the focus is on much more on understanding than in the previous categories, however this focus is on understanding how to use the information in order to carrying out algorithmic calculations which may be encountered outside class or in an exam situation. Within the category overall view of everything the focus is on linking the information or knowledge that is obtained through interactions with the lecturer and classmates in order to achieve success in the programme. The learning environment itself is an important feature of this category as it serves to develop this overall view of all that learning physics entails. There does not appear to be awareness of how this knowledge is useful outside of the learning environment. Within the understand category the focus is on understanding and interpreting the conceptual nature of physics and there is awareness that this understanding will lead to explanations of the physical world.

These themes of expanding awareness highlight the hierarchical shift within the categories from a perception of the learning environment that would appear to encourage a surface

approach to learning to a perception which would appear to encourage a deep approach (Marton & Säljö, 1976).

The implications of this work within the context of the research presented within the body of this thesis will be explored in detail through further work in this area.

APPENDIX G: Ethics Statement

ETHICS STATEMENT

As an education researcher, I realise that I am in a position of responsibility and trust, and this statement aims to show this.

“Whilst carrying out this research, I will observe the highest possible ethical standards. I will maintain integrity at all times regarding data gathering. I will only report information that is in the public domain and within the law. I will avoid plagiarism and fully acknowledge the work of others to which I have referred to in this study. I will report my findings honestly. I consider the research project worthwhile and of benefit to the academic staff and students with whom I work.

The permission of all the participants will be sought from each individual participant prior to any data collection. The identity of all undergraduate and postgraduate participants will remain anonymous in any and all disseminations of this research.

This research is designed to operate within an ethic of respect for any persons involved directly or indirectly in the research process, regardless of age, sex, race, religion, political beliefs, and lifestyle.

I recognise the importance of all participants in the research understanding the process in which they are to be engaged, including why their participation is necessary, how it will be used and how and to whom it will be reported.

I recognise the right of any participant to withdraw from the research for any or no reason, and at any time, and I will inform them of this right.

I intend to debrief participants at the conclusion of the research, to provide participants with copies of talk aloud protocol recordings and make available any reports or other publications arising from their participation.”

Laura Walsh

Physics Education Research Group

School of Physics

Dublin Institute of Technology

Kevin Street

Dublin 8

Ireland.

I,, have read the above ethics statement and agree to participate in the research outlined by Laura Walsh

Signed.....

Date.....

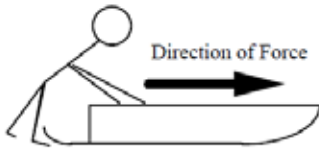

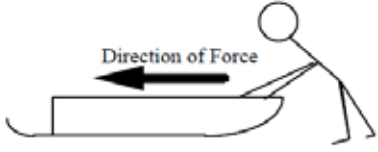
APPENDIX H: Force and Motion Conceptual Evaluation

FORCE AND MOTION CONCEPTUAL EVALUATION

Directions: Answer questions 1-47 in spaces on the answer sheet. Be sure your name is on the answer sheet. Answer question 46a also on the answer sheet. Hand in the questions and the answer sheet.

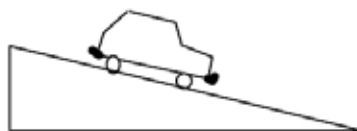
A sled on ice moves in the ways described in questions 1-7 below. *Friction is so small that it can be ignored.* A person wearing spiked shoes standing on the ice can apply a force to the sled and push it along the ice. Choose the one force (A through G) which would **keep the sled moving** as described in each statement below.

You may use a choice more than once or not at all but choose only one answer for each blank. If you think that none is correct, answer choice J.

	<p>A. The force is toward the right and is increasing in strength (magnitude).</p> <p>B. The force is toward the right and is of constant strength (magnitude).</p> <p>C. The force is toward the right and is decreasing in strength (magnitude).</p>
	<p>D. No applied force is needed</p>
	<p>E. The force is toward the left and is decreasing in strength (magnitude).</p> <p>F. The force is toward the left and is of constant strength (magnitude).</p> <p>G. The force is toward the left and is increasing in strength (magnitude).</p>

- ___1. Which force would keep the sled moving toward the right and speeding up at a steady rate (constant acceleration)?
- ___2. Which force would keep the sled moving toward the right at a steady (constant) velocity?
- ___3. The sled is moving toward the right. Which force would slow it down at a steady rate (constant acceleration)?
- ___4. Which force would keep the sled moving toward the left and speeding up at a steady rate (constant acceleration)?
- ___5. The sled was started from rest and pushed until it reached a steady (constant) velocity toward the right. Which force would keep the sled moving at this velocity?
- ___6. The sled is slowing down at a steady rate and has an acceleration to the right. Which force would account for this motion?
- ___7. The sled is moving toward the left. Which force would slow it down at a steady rate (constant acceleration)?

Questions 8-10 refer to a toy car which is given a quick push so that it rolls up an inclined ramp. After it is released, it rolls up, reaches its highest point and rolls back down again. *Friction is so small it can be ignored.*



Use one of the following choices (A through G) to indicate the **net force** acting on the car for each of the cases described below. Answer choice J if you think that none is correct.

- | | | |
|----------------------------------------------------------------------|--------------------------------------------------------------------|--------------------------------------------------------------------|
| <input type="radio"/> A Net constant force down ramp | <input type="radio"/> E Net constant force up ramp | |
| <input type="radio"/> B Net increasing force down ramp | <input type="radio"/> D Net force zero | <input type="radio"/> F Net increasing force up ramp |
| <input type="radio"/> C Net decreasing force down ramp | <input type="radio"/> G Net decreasing force up ramp | |

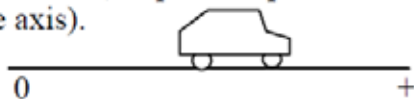
- _____ 8. The car is moving up the ramp after it is released.
_____ 9. The car is at its highest point.
_____ 10. The car is moving down the ramp.

Questions 11-13 refer to a coin which is tossed straight up into the air. After it is released it moves upward, reaches its highest point and falls back down again. Use one of the following choices (A through G) to indicate the force acting on the coin for each of the cases described below. Answer choice J if you think that none is correct. **Ignore any effects of air resistance.**

- A. The force is **down** and constant.
- B. The force is **down** and increasing
- C. The force is **down** and decreasing
- D. The force is zero.
- E. The force is **up** and constant.
- F. The force is **up** and increasing
- G. The force is **up** and decreasing

- _____ 11. The coin is moving upward after it is released.
_____ 12. The coin is at its highest point.
_____ 13. The coin is moving downward.

Questions 14-21 refer to a toy car which can move to the right or left along a horizontal line (the positive part of the distance axis).

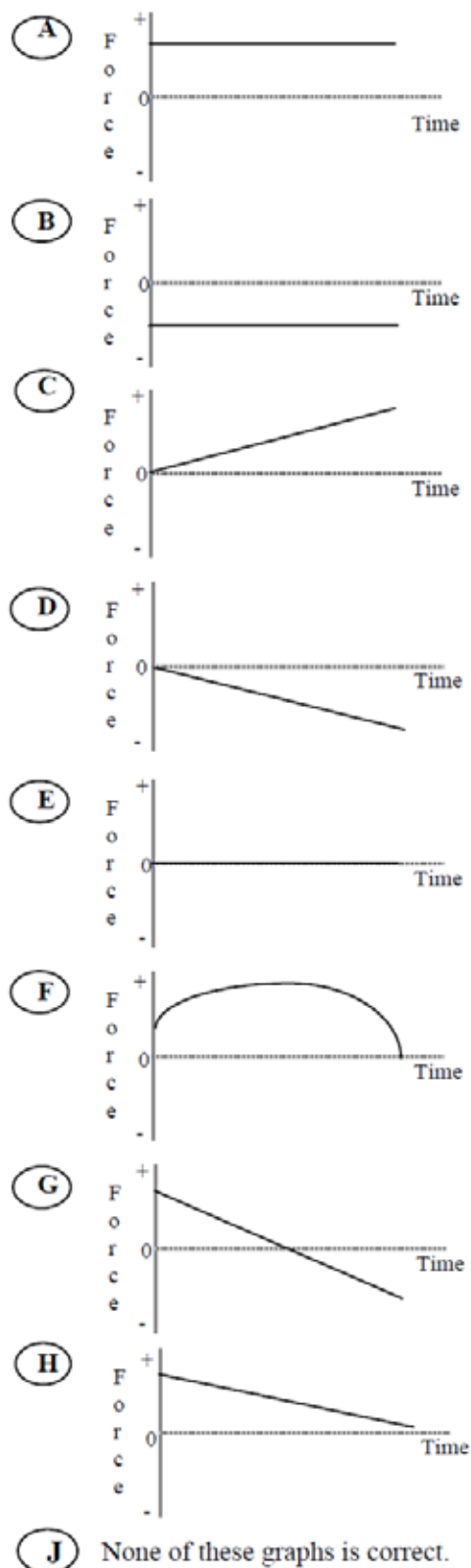


Assume that friction is so small that it can be ignored.

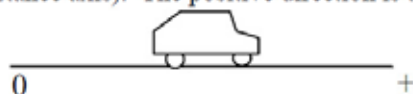
A force is applied to the car. Choose the one force graph (A through H) for each statement below which could allow the described motion of the car to continue.

You may use a choice more than once or not at all. If you think that none is correct, answer choice J.

- ___ 14. The car moves toward the right (away from the origin) with a steady (constant) velocity.
- ___ 15. The car is at rest.
- ___ 16. The car moves toward the right and is speeding up at a steady rate (constant acceleration).
- ___ 17. The car moves toward the left (toward the origin) with a steady (constant) velocity.
- ___ 18. The car moves toward the right and is slowing down at a steady rate (constant acceleration).
- ___ 19. The car moves toward the left and is speeding up at a steady rate (constant acceleration).
- ___ 20. The car moves toward the right, speeds up and then slows down.
- ___ 21. The car was pushed toward the right and then released. Which graph describes the force after the car is released.

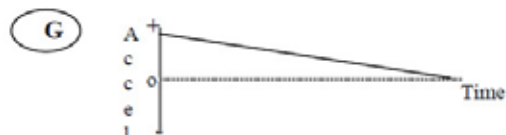
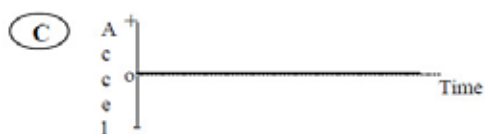
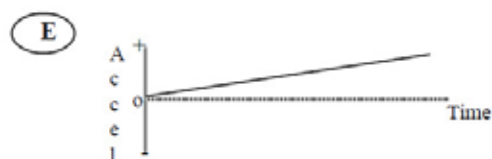


Questions 22-26 refer to a toy car which can move to the right or left on a horizontal surface along a straight line (the + distance axis). The positive direction is to the right.



Different motions of the car are described below. Choose the letter (A to G) of the **acceleration-time** graph which corresponds to the motion of the car described in each statement.

You may use a choice more than once or not at all. If you think that none is correct, answer choice J.



(J) None of these graphs is correct.

- ___ 22. The car moves toward the right (away from the origin), speeding up at a steady rate.
 ___ 23. The car moves toward the right, slowing down at a steady rate.
 ___ 24. The car moves toward the left (toward the origin) at a constant velocity.
 ___ 25. The car moves toward the left, speeding up at a steady rate.
 ___ 26. The car moves toward the right at a constant velocity.

Questions 27-29 refer to a coin that is tossed straight up into the air. After it is released it moves upward, reaches its highest point and falls back down again. Use one of the following choices (A through G) to indicate the acceleration of the coin during each of the stages of the coin's motion described below. Take **up** to be the **positive** direction. Answer choice **J** if you think that none is correct.

- A. The acceleration is in the negative direction and constant.
- B. The acceleration is in the negative direction and increasing
- C. The acceleration is in the negative direction and decreasing
- D. The acceleration is zero.
- E. The acceleration is in the positive direction and constant.
- F. The acceleration is in the positive direction and increasing
- G. The acceleration is in the positive direction and decreasing

- ___27. The coin is moving upward after it is released.
- ___28. The coin is at its highest point.
- ___29. The coin is moving downward.

Questions 30-34 refer to collisions between a car and trucks. For each description of a collision (30-34) below, choose the one answer from the possibilities **A** through **J** that best describes the forces between the car and the truck.

- A. The truck exerts a greater amount of force on the car than the car exerts on the truck.
- B. The car exerts a greater amount of force on the truck than the truck exerts on the car.
- C. Neither exerts a force on the other; the car gets smashed simply because it is in the way of the truck.
- D. The truck exerts a force on the car but the car doesn't exert a force on the truck.
- E. The truck exerts the same amount of force on the car as the car exerts on the truck.
- F. Not enough information is given to pick one of the answers above.
- J. None of the answers above describes the situation correctly.

*In questions 30 through 32 the truck is **much heavier** than the car .*



- ___30. They are both moving at the same speed when they collide. Which choice describes the forces?
- ___31. The car is moving much faster than the heavier truck when they collide. Which choice describes the forces?
- ___32. The heavier truck is standing still when the car hits it. Which choice describes the forces?

In questions 33 and 34 the truck is a small pickup and is the *same weight* as the car.



- ____ 33. Both the truck and the car are moving at the same speed when they collide. Which choice describes the forces?
- ____ 34. The truck is standing still when the car hits it. Which choice describes the forces?

Questions 35-38 refer to a large truck which breaks down out on the road and receives a push back to town by a small compact car.



Pick one of the choices **A** through **J** below which correctly describes the forces between the car and the truck for each of the descriptions (35-38).

- A.** The force of the car pushing against the truck is equal to that of the truck pushing back against the car.
- B.** The force of the car pushing against the truck is less than that of the truck pushing back against the car.
- C.** The force of the car pushing against the truck is greater than that of the truck pushing back against the car.
- D.** The car's engine is running so it applies a force as it pushes against the truck, but the truck's engine isn't running so it can't push back with a force against the car.
- E.** Neither the car nor the truck exert any force on each other. The truck is pushed forward simply because it is in the way of the car.
- J.** None of these descriptions is correct.
- ____ 35. The car is pushing on the truck, but not hard enough to make the truck move.
- ____ 36. The car, still pushing the truck, is **speeding up** to get to cruising speed.
- ____ 37. The car, still pushing the truck, is at cruising speed and continues to travel at the **same speed**.
- ____ 38. The car, still pushing the truck, is at cruising speed when the truck puts on its brakes and causes the car to **slow down**.

39. Two students sit in identical office chairs facing each other. Bob has a mass of 95 kg, while Jim has a mass of 77 kg. Bob places his bare feet on Jim's knees, as shown to the right. Bob then suddenly pushes outward with his feet, causing both chairs to move. In this situation, while Bob's feet are in contact with Jim's knees,

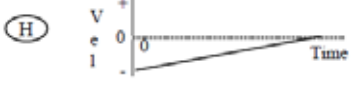
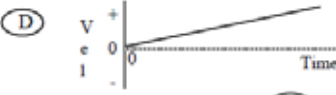
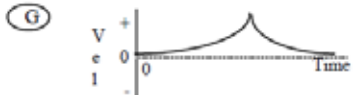
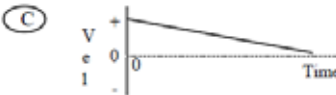
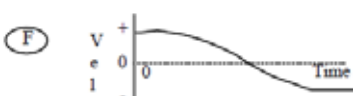
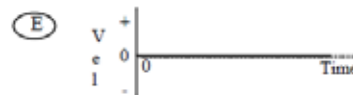
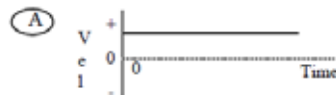


- A. Neither student exerts a force on the other.
 B. Bob exerts a force on Jim, but Jim doesn't exert any force on Bob.
 C. Each student exerts a force on the other, but Jim exerts the larger force.
 D. Each student exerts a force on the other, but Bob exerts the larger force.
 E. Each student exerts the same amount of force on the other.
 J. None of these answers is correct.

Questions 40-43 refer to a toy car which can move to the right or left along a horizontal line (the positive portion of the distance axis). The positive direction is to the right.



Choose the correct velocity-time graph (A - G) for each of the following questions. You may use a graph more than once or not at all. If you think that none is correct, answer choice J.



(J) None of these graphs is correct.

40. Which velocity graph shows the car moving toward the right (away from the origin) at a steady (constant) velocity?
 41. Which velocity graph shows the car reversing direction?
 42. Which velocity graph shows the car moving toward the left (toward the origin) at a steady (constant) velocity?
 43. Which velocity graph shows the car increasing its *speed* at a steady (constant) rate?



A sled is pulled up to the top of a hill. The sketch above indicates the shape of the hill. At the top of the hill the sled is released from rest and allowed to coast down the hill. At the bottom of the hill the sled has a speed v and a kinetic energy E (the energy due to the sled's motion). Answer the following questions. *In every case friction and air resistance are so small they can be ignored.*

- _44. The sled is pulled up a **steeper** hill of the **same** height as the hill described above. How will the velocity of the sled at the bottom of the hill (after it has slid down) compare to that of the sled at the bottom of the original hill? Choose the best answer below.
- A. The speed at the bottom is **greater** for the steeper hill.
 - B. The speed at the bottom is the same for both hills.
 - C. The speed at the bottom is **greater** for the original hill because the sled travels further.
 - D. There is not enough information given to say which speed at the bottom is faster.
 - J. None of these descriptions is correct.
- _45. Compare the kinetic energy (energy of motion) of the sled at the bottom for the original hill and the steeper hill in the previous problem. Choose the best answer below.
- A. The kinetic energy of the sled at the bottom is **greater** for the steeper hill.
 - B. The kinetic energy of the sled at the bottom is the same for both hills.
 - C. The kinetic energy at the bottom is **greater** for the original hill.
 - D. There is not enough information given to say which kinetic energy is greater.
 - J. None of these descriptions is correct.
- _46. The sled is pulled up a **higher** hill that is **less** steep than the original hill described before question 44. How does the speed of the sled at the bottom of the hill (after it has slid down) compare to that of the sled at the bottom of the original hill?
- A. The speed at the bottom is **greater** for the higher but less steep hill than for the original.
 - B. The speed at the bottom is the same for both hills.
 - C. The speed at the bottom is **greater** for the original hill.
 - D. There is not enough information given to say which speed at the bottom is faster.
 - J. None of these descriptions is correct.
- 46a. Describe in words your reasoning in reaching your answer to question 46. (**Answer on the answer sheet** and use as much space as you need)
- _47. For the higher hill that is less steep, how does the kinetic energy of the sled at the bottom of the hill after it has slid down compare to that of the original hill?
- A. The kinetic energy of the sled at the bottom is **greater** for the higher but less steep hill.
 - B. The kinetic energy of the sled at the bottom is the same for both hills.
 - C. The kinetic energy at the bottom is **greater** for the original hill.
 - D. There is not enough information given to say which kinetic energy is greater.
 - J. None of these descriptions is correct.

