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REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
ON............7 December 2001..................
................[redacted]...
Sec. Research Graduate School Committee

Errata

p 11, l 15	"their origins" for "its nature"
p 31, l 5	"Giotto" for "Gioto"
p 31, l 6	"stamps (cf. Figure 2.2)" for "stamps"
p 42, l 12	"to" for "left to"
p 57, l 13	"antinomy" for "antimony"
p 72, l 12	"it" for "is"
p 72, l 19	"process" for "processes"
p 88, l 17	"Aristotle" for "he"
p 89, l 7	"Aristotelian Model" for "Model"
p 110, l 15	"5.8" for "5.8z"
p 112, l 19	"that" for "the that"
p 142, l 11	"and" for "an"
p 169, l 10	"and" for "an"
p 211, l 2	"6.14" for 6.23" and "6.22" for "6.31"
p 229	"A32" for "32"
p 291, l 9	"7-20" for "7-19"
p 315, l 3	"Int" for "Stu"
p 315, l 17	"over resultant" for "over"
p 342, l 9	"due to" for "due"
p 358	"A1" for "1" in footnote
p 364	"2001" for "20001"
p 377, footnote	"the appendices" for "— as detailed in Section A.5"
p 397, l 17	"can be implemented" for "can implemented"
p 415, l 13	"2)" for "2"
p A-12, l 5	"This" for "The"
p R-31	"Microsoft, 2001" for "Microsoft, 20001"

Exploring Pedagogical Content Knowledge:

Design principles for PCK-enhanced software arising from student-teachers' understandings of gravity

by
Paul Stuart Nicholson
M.Sc., M.Ed (Studs)., Dip.App.Chem., TTTC

A dissertation submitted in fulfillment of the requirements for the degree of Doctor of Philosophy in the Faculty of Education, Monash University, Clayton, Australia

February 2001

Approved by the Standing Committee in Research on Humans
13 June 1995
Approval No. E5.38/95

We also need more pedagogical content knowledge research conducted in the context of teacher preparation programs per se, rather than in comparisons of novice and expert teachers or in comparisons of preservice and experienced teachers.

(Cochran & Jones, 1998, p.715)

M O N A S H U N I V E R S I T Y

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AUSTRALIA

MEMO

15 June 1995

A/Professor A McDougall
Graduate School of Education
CLAYTON CAMPUS

Re: E5.38/95 - Student-teachers' Understanding of Gravity

The Standing Committee on Ethics in Research on Humans at its meeting on 13 June 1995 approved the above project to proceed.

The project has been allocated a discrete number to assist us in maintaining records.

[redacted]

Lyn Gash
Secretary
Standing Committee on Ethics
in Research on Humans

Copy to: Mr P Nicholson
Faculty of Education
Deakin University
662 Blackburn Road
CLAYTON 3168

c:\education\mcdouga2

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Members of each of four cohorts of preservice science teachers were examined to determine their scientific content knowledge of gravity, and to look for evidence of emerging pedagogical content knowledge related to their classroom teaching of gravity in the senior secondary school curriculum. A fine-grained, semi-structured interview that made extensive use of media and computer-based probes, was used to collect detailed data about a narrow range of gravitational contexts relating to orbital motion and planetary gravity. Significant conceptual difficulties were identified, including several well known misconceptions. From the data, a knowledge base for teaching gravity was developed that addressed those conceptual problems. This was subsequently used to inform the development of a new genre of educational software, PCK-enhanced software, which can be used to address the conceptual and pedagogical problems identified in the participants of this thesis.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other institution. To the best of my knowledge, the thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

P. S. Nicholson

Acknowledgements

In the evolution of this thesis, a number of people have provide me with guidance and support, for which I am most grateful. I would like to first thank my family for their support and tolerance of a husband and father who at times seemed far more engaged with his computer than with them Without their encouragement and support, this work could never have reached it's end.

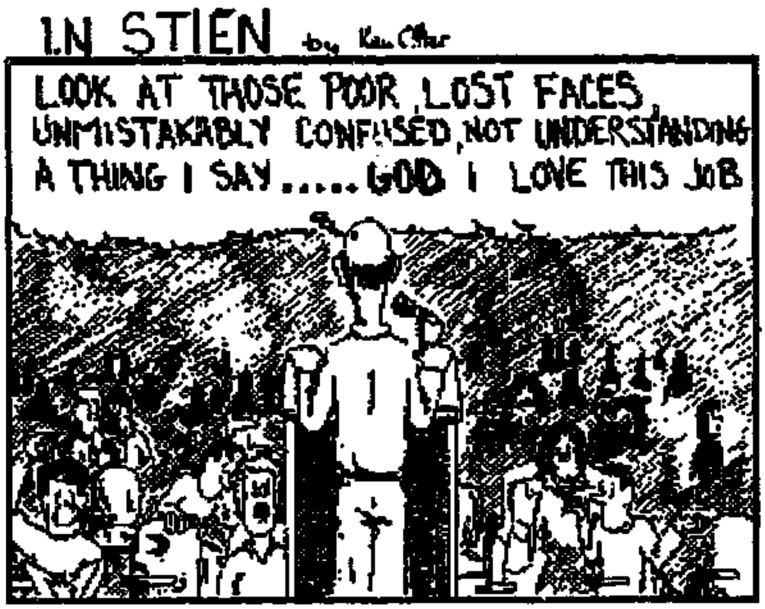
I wish to express special thanks to my original supervisor, Associate Professor Anne McDougall, for her initial support and encouragement, the entree she provided me with into the global community of educational computing researchers, her companionship on international flights and at conferences, and for her critical analysis of international coffee varieties.

My associate and subsequent supervisors, Professor Dick Gunstone, and Associate Professor John Loughran equally deserve my sincere thanks for their gentle guidance, the incisive viewpoints they provided me with, and for giving me the confidence and freedom to explore the intertwined fields that I have examined in this thesis. John deserves particular commendation for the encouragement, prompt reading, and critique of the final draft chapters that allowed me to complete this work.

To all of the above, I express my heartfelt gratitude.

Chapter 1

Introduction to the study



1

Introduction to the study

> The sagacious reader who is capable of reading between these lines what does not stand written in them, but is nevertheless implied, will be able to form some conception.
>
> Goethe, Autobiography. Book xviii. Truth and Beauty

1.1 Purpose

This thesis attempts to identify and articulate a *conceptual design* for a genre of software for use in science-teacher-education that embraces both conceptual *and* pedagogical development aspects (for preservice teachers) in a holistic, integrated fashion, in accordance with Shulman's notions (1984; 1986a; 1986b; 1999) of the intimate and interactive relationship between teachers' subject matter knowledge and Pedagogical Content Knowledge[1] (PCK).

The driving force behind this thesis comes from a perceived need for improving student learning[2] of both content knowledge and pedagogical knowledge in the author's science-teacher-education context[3]. This thesis explores the difficulties, both pedagogical and conceptual, that preservice science teachers have with a particular area of the Victorian (Australia) senior school physics curriculum, and seeks to find ways to remediate those difficulties through the development of a conceptual software design that is inclusive of both pedagogical and conceptual

1. Chapter 3 describes how this is defined in the context of this thesis.
2. of preservice science teachers.
3. See Section 2.1 on page 15.

development; a genre of software conceived for the purposes of this thesis, and which I have named 'PCK-enhanced'[4] software.

The focus on developing design principles for PCK-enhanced software stems partly from the author's experience with, and belief in the efficacy of, software in facilitating cognitive development (cf. Andaloro & Bellomonte, 1998; Andaloro, Bellomonte, & Sperandeo-Mineo, 1997; Brown, 1985; Chien, 1997; Cockburn & Greenberg, 1995; Dede, Salzman, & Bowen Loftin, 1996; diSessa, 1982, 1993a; diSessa & White, 1982; Ganiel & Idar, 1985; Gillies, Sinclair, & Swithenby, 1996; Goldberg, 1997; Greeno, 1991; Hennessy et al., 1990; Klopfer, 1986; Ogborn & Squires, 1987; White & Horwitz, 1987), and partly from Hestenes' (1995, p.63) call for the urgent development of design principles to facilitate the development of an 'integrated mathematics-science software curriculum', in which he argues that the lack of good curriculum software may lead to saturation with 'junk' software '...unless a clearly superior "software curriculum" is developed to displace it'. (p.63)

> Since junk software does not address fundamental pedagogical issues, it will exacerbate existing educational problems by diverting attention and resources. ... This impending software crisis can be averted if scientists, educators and software developers collaborate on the development of an integrated Mathematics-Science Software Curriculum which is pedagogically sound. We say "software curriculum" rather than "curriculum software", because we see it as agent for curriculum reform rather than an enhancement of the existing curriculum. (Hestenes, 1995, p.63)

Hestenes' is arguing for a software curriculum to enhance subject matter knowledge, because of a belief that software, when integral to the science curriculum[5], can foster the development of '... student cognitive development

4. The name that I have given to the genre of software that forms the focus of this thesis.

along a progression of competence levels'. (p.64) He also argues that integration across grade levels, and across subjects and disciplines will provide a comprehensive and holistic learning environment that will allow learners' knowledge to transcend subject boundaries. Berlin and White (1998) also argue the need for an integrated Mathematics and Science curriculum[6], but with the integrated, ubiquitous use of software adopted *into* the curriculum (cf. Chien, 1999; Koirala, Bowman, & Davis, 1999) so that science and mathematics '...can be integrated conceptually and procedurally in a meaningful and authentic format.' (p.507). Likewise, Roschelle, Digiano, Pea, and Kaput, (1999) argue for developing reusable 'Educational Software Components' to make software cheaper and more flexible, so that it can fit into more areas of the curriculum. Hestenes, however, argues that:

> Little curriculum reform can be expected from stand-alone software packages, no matter how brilliantly conceived. (Hestenes, 1995, p.64)

This implies that the creation of a new genre of educational software[7] is required. Such an ambitious goal, however, cannot be attained without the development of robust and tested principles to inform its development:

> An integrated mathematics-science software curriculum cannot be achieved without a broad consensus amongst its developers on design principles, guidelines and specifications which promote integration without limiting the creativity of individual developers. ... The software designs must be grounded in a coherent theory of scientific knowledge, including its use and acquisition.(Hestenes, 1995, p.64)

Hestenes clearly recognises the magnitude of this task:

5. Hence the term 'software curriculum'.

6. through the development of a theoretical model to inform practice.

7. A term inclusive of software-based learning *environments*.

> We invite like-minded colleagues to join us in the immense and exciting task of integrated mathematics-science software design and development. (Hestenes, 1995, p.64)

This 'invitation' is essentially the aim of this thesis[8] — by exploring a microcosm of this task through the development of a conceptual design for PCK-enhanced science-education software within a narrow, carefully defined context, and with limited content, this exploratory research attempts to illuminate some of the dimensions of this 'immense and exciting' task.

The contemporary relevance and importance of research such as this that focuses on 'cross knowledge base' research has recently been recognised and emphasised (in different terms) by the National Science Foundation (USA) in the context of Knowledge and Distributed Intelligence (KDI), and Learning and Intelligent Systems (LIS) (Sabelli, 1999), as well as in developing high quality science and mathematics education programs (National Science Foundation, 2000). Both KDI and LIS emphasize '...the integration of theory with experiments that ground, test, and advance basic understanding of learning and intelligent behaviour', which is essentially the area that this thesis is attempting to address.

> **As I have *attempted* in this thesis, such cross knowledge base research aims to create new understandings of existing and emerging contexts and issues from a synthesis of what have all *too often* been compartmentalised ideas, paradigms, and data.**

While Hestenes is essentially arguing about enhancing the learning of subject matter knowledge, in Teacher Education there is a well articulated need to ensure

8. Particularly in the longer term.

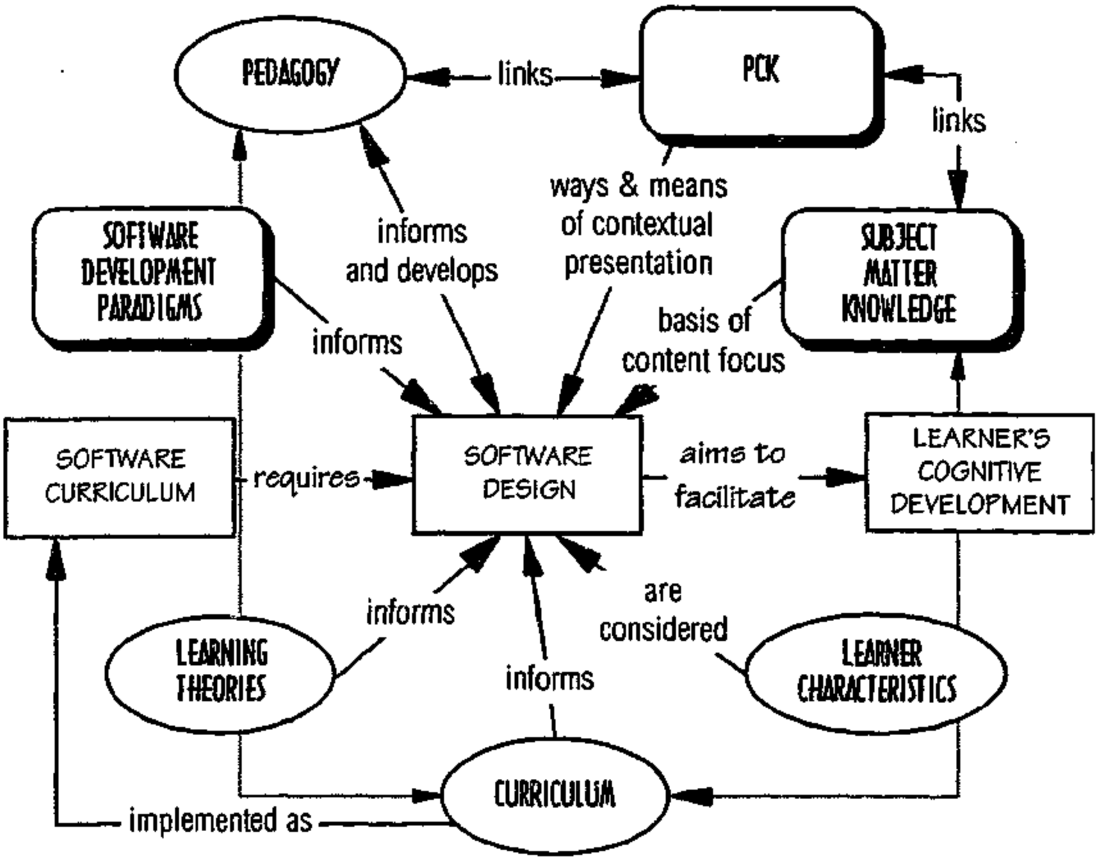
that the development of pedagogical knowledge occurs concurrently with subject matter knowledge (e.g., Cochran & Jones, 1998; Niess & Scholz, 1999; NSTA, 1999). In the case of a software curriculum for Teacher Education, the inclusion of ways and means of developing pedagogical content knowledge is therefore essential — a position at the heart of this thesis.

1.2 The Challenge

Hestenes' invitation presents enormous challenges to educators and software developers. In Hestenes' software curriculum notion, it is inferred that the software learning environment links teachers and learners with subject matter knowledge through a pedagogy that is also intrinsically intertwined with the nature and design of the software environment as depicted in Figure 1-1 below[9]— a general conceptual model of some of the entities that need to be included in developing software in accordance with Hestenes' notion of a software curriculum. This is not necessarily the only possible model, but rather, a first-order approximation to what a fully developed model might include when fully informed by research and experience with, and in, such environments. The magnitude of the task of attempting to address all of the areas across a complete software curriculum program from, say, years seven to ten, or even for a complete year level is too great to be feasible without tested, robust guidelines and design principles in place.

9. The three shadowed symbols are the areas explicitly examined in this thesis.

Figure 1-1: General conceptual relationship between pedagogy, technology, and curriculum developed from Hestenes' software curriculum description (Hestenes, 1995, p.64).



This thesis attempts to explore and articulate a microcosm of this task by examining what the *attributes* of PCK-enhanced software[10] for teaching a small area of the senior physics curriculum might look like — what types of entities might need to be included (based on the research conducted in this thesis), and then goes on to consider how this might be used as the foundation of a design for PCK-enhanced software as an element of Hestenes' software curriculum, and what features such a design might have incorporated in it. This attempt to articulate a conceptual design for PCK-enhanced software is a small, but significant, step towards addressing Hestenes' invitation to create more effective, and integrated, software learning

10. i.e., a focus on pedagogical aspects — as opposed to subject matter knowledge.

environments in which preservice science and mathematics educators can develop holistic understandings of both subject matter knowledge, and its relation to, and interactions with, pedagogical content knowledge. The actual development and trialing of such software will form the focus of a subsequent study.

1.3 The Process

This thesis represents a synthesis of literature from a number of research fields including:

1. conceptual development and misconceptions in science education;
2. teacher education and pedagogical content knowledge;
3. computer-based learning environment design, including artificial intelligence aspects and cognitive science.

This cross-field synthesis aims to '...organize knowledge in new ways, integrate previously disparate findings, suggest explanations, stimulate reseach, and reveal new relationships.' (Gess-Newsome, 1999, p.3) Each of the three items above are important aspects of the relationships shown in Figure 1-1, and in particular, form much of the content of the three shadowed symbols in that figure. Each of the three areas — subject matter knowledge, PCK, and software design paradigms, are examined in this thesis.

The PCK literature (reviewed in Chapter 3) in conjunction with the conceptual and 'misconceptions' literature (reviewed in Chapter 4) provides the foundation for an examination of the science content knowledge and PCK of the participants of this thesis through the use of a semi-structured interview. This forms the substantive basis of the research described in Chapters 3 - 7 that seeks to determine the nature of the participants' problems with the content area under examination. The PCK literature forms the basis for relating content knowledge to practice, and hence to understanding how teachers' PCK might be understood, documented, and 'recreated' in software. The cognitive science and artificial intelligence literature provides suggestions as to how the content knowledge-PCK relationship might be understood and developed at the software design level. The contemporary learning environment design literature provides significant insights into how 'teaching' and pedagogy might be implemented in ways that are beginning to accommodate the contextually sensitive, individualised, and customised ways that characterise contemporary views of effective teaching. In chapter 8, a synthesis of these different literatures is attempted, in conjunction with the findings of the research described herein, in order to tease out a prototype conceptual design for a software environment that would fit Hestenes' proposed software curriculum model.

In accordance with Tobin & Fraser's guidelines for exploratory research (1998), this thesis adopts a qualitative, interpretive methodology to raise and illuminate potential issues, rather than attempting to be a definitive comprehensive quantitative study of the factors that need to be considered in developing a software environment for a software curriculum, particularly when the latter is ill-defined. Tobin and Fraser recommend the use of qualitative study for exploratory research (i.e., where the aim is to 'flesh out' the parameters or key aspects of an issue or field, rather than to test a specific hypothesis or treatment) — as in this thesis — as a precursor to subsequent quantitative studies based on the findings of such prior exploratory research:

> Before quantification, it is desirable to illuminate salient constructs with investigations of broad questions like those typically addressed in interpretive research. Later, quantification of the constructs can enable a larger range of questions to be answered. (Tobin & Fraser, 1998, p.625)

This is the position that has been adopted for this thesis, and that which informs both the research described in this thesis, and the subsequent efforts to develop a conceptual design for a PCK-enhanced software environment to support a software curriculum.

1.4 Foci

This section briefly identifies the significance of each of the three areas explicitly examined in this thesis. Each area is developed further in the body of the thesis.

1.4.1 A focus on subject matter knowledge

Cochran & Jones (1998) note that the development of science teachers' subject matter knowledge has received scant attention from researchers:

> Until recently, little attention has been paid to the development of science subject matter knowledge in preservice teachers. The implicit assumption is that an undergraduate degree in a subject area or related area (and relevant pedagogical preparation) provides an adequate basis for teaching. (Cochran & Jones, 1998, p.707)

and further, that:

> Studies are starting to provide evidence that subject matter knowledge, by itself, is not enough preparation for teaching. (Cochran & Jones, 1998, p.707)

The 'implicit assumption' (above) is at the core of this thesis, providing both the context and content for the exploration of Hestenes' invitation (see Chapter 2 for details). Dykstra Jr. provides support for this claim from the more general perspective of science majors (as opposed to teacher educators) in referring to misconceptions research conducted over the past 30 years:

> What we have been finding consistently is that student conceptions hardly if at all change as a result of normal science instruction. For example even though students in the US have had instruction which should affect their answers to the following questions and many, many others, even students who are graduates of the most prestigious Universities, who are not science majors, still answer the questions in the same fashion conceptually as their elementary school peers. (Dykstra Jr, 2000)

The research described in Chapters 5-7, in which preservice science teachers' understandings of subject matter knowledge of a selected aspect of physics are examined through a fine-grained qualitative study (Tobin & Fraser, 1998, p.627) that attempts to determine the nature of their difficulties in teaching physics that arise from both pedagogical (i.e., PCK) and subject matter knowledge issues.

In accordance with Cochran & Jones' concerns (1998), the data collected in this research shows that the majority of the participants of this study have poor understandings of the relevant subject matter knowledge, which is poorly understood, inconsistently applied and represented (cf. McDiarmid, Ball, & Anderson, 1989; Zembal-Saul, Starr, & Krajcik, 1999, p.237).

1.4.2 A focus on PCK

In accordance with both Shulman's formulation of the intimate relationship between subject matter knowledge and Pedagogical Content Knowledge (PCK), and an increasing interest in it's relationship to effective science teaching (e.g., Carlsen, 1991; Shulman, 1999), the thesis also looks for evidence of related emerging pedagogical content knowledge:

> We also need more pedagogical content knowledge research conducted in the context of teacher preparation programs per se, rather than in comparisons of novice and expert teachers or in comparisons of preservice and experienced teachers. (Cochran & Jones, 1998, p.715)

The specific aspect of PCK that this thesis focuses on is how the participants can make their subject matter knowledge comprehensible to their students — 'The most useful forms of (content) representation..., the most powerful analogies, illustrations, examples, explanations, and demonstrations — in a word, the ways of representing and formulating the subject that makes it comprehensible to others' (Shulman, 1986b, p.9). If teachers are not able to do this, then an excellent grasp of subject matter knowledge is not likely to be translated into clear and effective pedagogy. The research in this thesis, in part, seeks to determine the ways in which the participants explain their understandings of the physics context, in an effort to gain insight into its nature, and to inform strategies that might make improve upon them.

1.4.3 A focus on software development

Since Abelson, Feurzeig, and Papert (e.g., Abelson, 1982; Abelson, 1984; Feurzeig & Lukas, 1972; Papert, 1973, 1984, 1985) first popularised the use of software as a cognitive and representational tool based generally on Piagetian constructivism, a genre of educational software development has developed[11], which, to varying

11. Generally based on a computational paradigm based around a derivative of the Logo programming language.

degrees, accommodates a range of Piagetian and post-Piagetian constructivist psychological models in an attempt to provide effective constructivist software-based learning environments (cf. Clayson, 1988; Hammond, 1984; Harel, 1991; McDougall, 1988; Resnick, 1992; Silvermann, 1993; Squires & Sellman, 1986; Trimble, 1986; Watt, 1989; Weir, 1987). Such learning environments are predicated on the assumption that the learner is an active constructor of knowledge, and increasingly, as part of a community of learners seeking to develop their understandings as a group (cf. Brown et al., 1993; Putnam & Borko, 2000, p.5; Salomon, 1993).

Contemporary software development commonly incorporates features which are not widely employed in the software genre described above, with pedagogical agents, distributed systems, advanced representational formats such as Virtual Reality, streaming video, and data visualisation becoming increasingly common. In non-educational sectors, these features are being employed to facilitate communication, improve understandings of complex, fuzzy ideas (e.g., Nicholson, 1999; Nicholson & White, 2000c), and to enhance the ability of workers to cope with 'supercomplexity' in the workplace environment (Barnett, 1999).

The focus on software development in this thesis stems from both Hestenes' clarion call for such a focus, but also because of a belief that proven practices outside of common educational software development paradigms might have a lot to offer Education (e.g., Nicholson, 1999; Nicholson & Johnson, 1999; Nicholson & White, 2000b; 2000c), particularly in linking across knowledge domains such as content knowledge and PCK — a task that is, arguably, increasingly being seen as 'supercomplex' (cf. Gess-Newsome & Lederman, 1999).

1.5 The Structure of the Thesis

The structure of the thesis is given here as an 'advance organiser' for the reader so as to make explicit the nature and sequence of the following chapters:

1. Chapter one is an introduction to the study. It outlines the nature and origins of the research, its conceptual underpinnings, and the structure of the thesis.

2. Chapter two provides an overview of the nature and purpose of the study, and its origins in the author's professional context, and introduces the conceptual frameworks that are at the heart of the research in this thesis. It also details the context and content area of the study, and its significance. Participants' details, and their context for involvement in this thesis are discussed.

3. Chapter three examines the nature of PCK and develops issues of relevance to this thesis

4. Chapter four examines selected research on physics learning in the area of Newtonian mechanics and gravity that is of relevance to the VCE physics area of study that this thesis focuses on.

5. Chapter five examines the methodological issues of relevance to the development and conduct of the interview phase of this study.

6. Chapter six discusses the instruments employed in the interview phase of the research, examining their purpose, nature, design, and limitations. The specific details of all items used are described later in the appendices.

7. Chapter seven describes the data collected in the study from each of the participants, and presents a concurrent semantic analysis of that data.

8. Chapter eight is concerned with developing principles to inform the design

of PCK-enhanced software, and how such software might be implemented in order to assist preservice science teachers in overcoming the kinds of difficulties identified in the participants of this study. It is a synthesis of the literature reviewed in chapters 3, 4, the research described in Chapters 5-7, and the literature on contemporary software design.

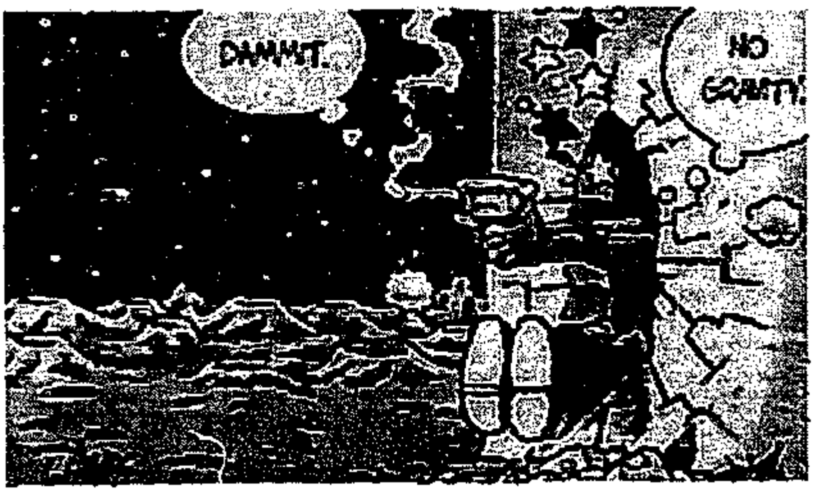
9. Chapter nine presents the conclusions and recommendations of this research.

1.6 Chapter Review

This chapter described the purpose of this research, and its origins in both Teacher Education, and in Hestenes' call for a software-driven paradigm shift in science education programs. It outlined the research process, presents challenges faced in this work, and described the specific foci that this research addresses. The structure of the thesis was described, with the items above being related to particular chapters of the dissertation.

Chapter 2

Background and context



2

Background and context

> When confronted with qualitative problems, most of which scarcely appear tricky or out of the range of basic understanding, students offer descriptions and solutions that are inconsistent with, and often in direct contradiction to, basic physics principles.
>
> (diSessa, 1993b, p1)

2.1 Origins

This thesis grew out of my involvement in physics-teacher education[1] where I frequently found evidence of serious misunderstandings, and weak, or inadequate explanations and representations of the physics concepts of gravity and gravitational field in my undergraduate preservice physics-education students. First, in their practicum placements[2] in schools they were often unable to give satisfactory answers in response to simple questions from students, preferring instead to rely on formulae and graphs (cf. Sanders, Borko, & Lockard, 1993). diSessa (1993b, p.1) suggests that such problems are common across the sciences, and argues, from the perspective of situated cognition, that the situations being reasoned about shape the kind of explanation that an individual will offer. Second, in addition to their inadequate explanations, I found many examples of incorrect

1. As a science-education lecturer conducting fourth year university physics-teaching methodology classes.
2. Classroom teaching experiences under the guidance of a qualified teacher.

statements, invalid metaphors, and wrong 'factual[3]' information being used in their classes (cf. Bischoff, Hatch, & Watford, 1999).

Similar conceptual difficulties with articulating and applying a wide range of physics concepts are well documented in the literature (e.g. Clement, 1982; Duit, 1993; Duit, Goldberg, & Niedderer, 1992; Duit & Pfundt, 2000; Gilbert & Watts, 1983; McCloskey, 1982, 1983a, 1983b; McCloskey, Kohl, & Wasburn, 1981; McDermott & Redish, 1999; Van Hise, 1988), and have generated a plethora of studies about their nature (e.g. Carmichael, 1990; Driver, 1990; Duit et al., 1992; Duit & Pfundt, 2000; Dykstra Jr, Monte, & Schroeder, 1994; Maloney, 1994; McDermott & Redish, 1999; Van Hise, 1988), origins (e.g. Braghiroli, 1993), and potential means of remediation. (e.g. Berliner, 1987; Gil-Perez & Carrascosa, 1990; Stepans, Beiswenger, & Dyche, 1986; Wandersee, 1985). Similar conceptual problems are also found in teachers who have not formally studied physical sciences; caused by their subject matter knowledge not being able to meet curriculum expectations (Kruger, Palacio, & Summers, 1992).

This category of conceptual difficulty has been referred to by a variety of names, such as 'preconceptions' (Ausubel, 1968), 'naive conceptions' (e.g. Champagne, Gunstone, & Klopfer, 1983), 'misconceptions' (Berliner, 1987; McCloskey, 1983a; Osborne, Bell, & Gilbert, 1983), 'alternate frameworks' (Watts, 1982), 'intuitive conceptions' (Eylon & Linn, 1988; Fischbein, 1994, p.43) and 'developmental levels' (Mali & Howe, 1979; Nussbaum, 1979), with each having a subtly different meaning depending on the researcher's conception of cognitive development,

3. i.e. facts presented or explained incorrectly or out of context.

concepts, and learning (Abimbola & Yarroch, 1993; Duit, 1993; Gilbert & Watts, 1983; White, 1990).

The term 'mental model' (Jonassen, 1995; Roschelle & Greeno, 1987; White, 1990) has been adopted by many researchers as a more inclusive term, and one which avoids '... the pejorative connotations of the older terms' (White, 1990, p.6), and that also accommodates a wide range of theoretical perspectives. It is often closely linked to cognitive science and information processing models and paradigms of cognition (e.g., Borgman, 1982), but this is historical, and not an essential attribute of the term as it is now employed in science education research. Fischbein (1994, p.44) suggests that such intuitive[4] understandings would possess, or be based on, some or all of the following characteristics:

- self-evidence (fundamental) - they are self-consistent and self-justifiable;
- intrinsic certainty (fundamental): they are accepted as certain;
- perseverance: robust over time and instruction;
- coerciveness: other alternatives are generally rejected;
- theory status: more than a 'skill' or 'the mere perception of a given fact';
- extrapolativeness: sometimes can be used to reach a conclusion on the basis of insufficient information than is normally needed;
- globalility: a 'global, synthetic view, as opposed to analytical thinking...';
- implicitness: they mask tacit processes and mechanisms.

My preservice teachers' problems with their understandings and explanations of mechanics and dynamics topics frequently led them into difficulties and oversights when teaching about gravity and other dynamics topics. They displayed these problems in two different situations — in junior school science classes where their emphasis was on descriptive explanations of physical phenomena, and also in

4. a term inclusive of the range of descriptors employed for 'misconceptions' as discussed above.

specialist senior physics classes where they were attempting to link theoretical, essentially mathematical, descriptions of motion in gravitational fields, with contextual examples drawn from the media, such as NASA images (NASA, 1994), television shows, and the popular press:

Interviewer: Where do you find gravity?
Joanna: Ah, right. Where do you find it? I don't know general questions like this! I'll roll off a formula if you like! Gravity... gravity acts on everything ... doesn't it?

(Thesis interview response by participant 'Joanna'[5])

This quote is a salient example of diSessa's point that opened this chapter. The actual motivation for this study is grounded in my frustration with the quality, accuracy and clarity of the classroom explanations that I observed in my student teachers (in the context of the above). Within a period of two days, I observed two physics lessons, each of which contained a significant amount of formal physics, but which were both devoid of effective communication about the topics being taught, and both of which contained dubious interpretations of the relevant physics. While these observations are not formally part of this thesis, in that they were gathered informally prior to its commencement, they are reported below to provide an insight into the issues that led to the genesis of this study.

2.1.1 Junior school science

The following dialogue from a student teacher's year ten science lesson on 'force' is a salient example of the type of problem that I frequently observed in the junior school context[6]. The student, 'Suzie'[7], has asked a question about falling objects

5. see Section 7.2.1 on page 246 for further responses.

after viewing an episode of the television cartoon series 'The Simpsons' the previous evening, in which she saw the character 'Homer' make an apparently impossible leap across a gorge[8] (FOX Television, 1992):

> 'Sir, why DO things fall down?' Suzie asked her science teacher.
> 'Ah…, um., because of gravity.' he answered.
> 'Yeah, that's what Dad said.' replied Suzie.
> 'Good! Are you sure you really understand?' the teacher added.
> 'Its cool - gravity does it.' was Suzie's reply.
> 'You've got it!' said the teacher.

After the class, I asked Suzie to explain what gravity was, or how it acted, or if she could explain why the leap she saw on television was impossible. She was unable to do so, but seemed happy with her knowledge that gravity made things fall down (cf. Arons, 1990, p.69). I also asked my preservice teacher if he thought that Suzie understood 'why things fall down?' He felt that she did! I left, feeling disappointed for both of them, and determined to identify ways for them to improve their knowledge of this aspect of physics. This event became both a context for, and subsequently, a focus of this thesis.

2.1.2 Senior physics

My concerns increased as I undertook clinical supervision of the preservice teachers' specialist physics practicum[9] during which they were teaching the gravitational topics in unit four of the Victorian Certificate of Education (VCE) senior physics syllabus (Board of Studies, 1994). The central ideas and context of

6. i.e., teaching general science topics in the years 7 - 10 curriculum.
7. a pseudonym to ensure anonymity.
8. cf. Arons, 1990, p.69
9. as described in Section 2.6.1 on page 40

the unit ‘Around the solar system’ are related to Newton’s law of universal gravitation, gravity, gravitational field and planetary systems[10]. Table 2-1 below lists the central ideas of the VCE unit four gravity context that forms the focus of this thesis.

Table 2-1: Central ideas of unit 4 gravity context (VBOS, 1997)

Newton’s insights into gravity have led to an understanding of the motion of the solar system, the achievements of space travel, and satellite technology.
• Newton’s law of universal gravitation. • Circular orbits under gravity. • Gravitational field. • Energy transfers from area under gravitational force-distance graphs. • Weight and apparent weight.

The preservice teachers that I observed were often unable to adequately answer some of the most basic questions from students about gravity and gravitational field (again, anecdotally reported here)...

Student: ‘What’s a gravitational field got to do with gravity?’
Teacher: ‘It’s where you find gravity.’
Student: ‘What do you mean?’
Teacher: ‘There is always a gravitational field between two planets.’
Student: ‘Oh, OK.’

In this dialogue there is potential confusion over where a gravitational field exists, no mention of their pervasive nature, nor of their form. By omission it has sown potential seeds of confusion between force, field and acceleration (i.e. gravity).

10. detailed in Section A.1 on page 1

Such partly correct answers were symptomatic of the students that I observed. In another discussion on orbital motion, one preservice teacher told the class...

> 'The laws of gravity only work for circular orbits'. (preservice-teacher)

At the same time, and in accordance with diSessa's comment that opens this chapter, their quantitative knowledge of the same situations was generally very good — they could describe how to solve all the relevant mathematical problems in the text with correct explanations, and described the use of the necessary equations quite effectively.

> **It was this disconnectedness of the two modes of their teaching that finally convinced me that a way to reconcile the differences had to be found. That was the origin of this thesis.**

2.2 The aim of the study

Much of the traditional research in science-teacher education has been based on the assumption that teachers' and students' problems with teaching or learning science, and especially physics, are largely due to partially or incorrectly formed understandings of the relevant concepts and laws, or of their relationship to one another. There is a rich literature about the specific conceptual models that learners hold, and strategies for 'remediation' through appropriate interventions or teaching strategies (e.g., Andaloro & Bellomonte, 1998; Andaloro, Bellomonte, & Spreandeo-Mineo, 1995; Dagher, 1994; Gowin, 1983; Halloun, 1998; Harrison & Treagust, 1994; Hestenes, 1995; Pines & West, 1983; Posner, 1983; Salyachivin, 1985; Sneider & Ohadi, 1998). Such research, however, essentially focuses only on scientific content knowledge acquisition, development, and use.

Shulman (1986a; 1986b), however, suggests that Pedagogical Content Knowledge (PCK) — teachers' special amalgam of subject knowledge and pedagogic skill that '...makes a subject comprehensible to others' (Shulman, 1987, p.9), is an equally important focus for educational research. This is a knowledge base for teaching (Grossman, Wilson, & Shulman, 1989) that encompasses the ways in which teachers' pedagogical knowledge and skills interact with their subject content knowledge to produce contextually and developmentally appropriate teaching strategies, explanations and descriptions of content matter. It is currently considered to be an important knowledge base for science teacher preparation (e.g., NSTA, 1999; Tobias, 1999; Veal & MaKinster, 1999, p.1).

While being a valuable guiding construct, detailed understandings about the nature of PCK are still developing (e.g., Carlsen, 1999, p.134; Loughran, Gunstone, Berry, Milroy, & Mulhall, 2000, p.2). Noting that previous models of PCK in science education had not been structured as taxonomies (Cochran, King, & DeRuiter, 1991), Veal and Makinster (1999) have proposed a General *Taxonomy* of PCK for science education so as to identify and characterize PCK studies to a functional (as opposed to theoretical) framework with three hierarchical levels:

- *General* PCK — a more specific category than pedagogy, with processes related to specific disciplines;
- *Domain-specific* PCK — relates to practices within and across a specific domain or subject area within a discipline (such as physics, biology);
- *Topic-specific* PCK — relates to aspects of topic-specific practice (such as gravity, oxidation, or genetics).

This general taxonomy is useful in classifying a wide range of PCK studies that do not necessarily share a common set of attributes or characteristics of PCK. Shulman's model raises the issue that it might be the nature and quality of teachers' PCK that is the cause of many of the observed difficulties in teaching and learning, such as the disconnectedness of the modes of my preservice teachers' teaching, rather than their content knowledge, and provides a framework for examining this dichotomy[11].

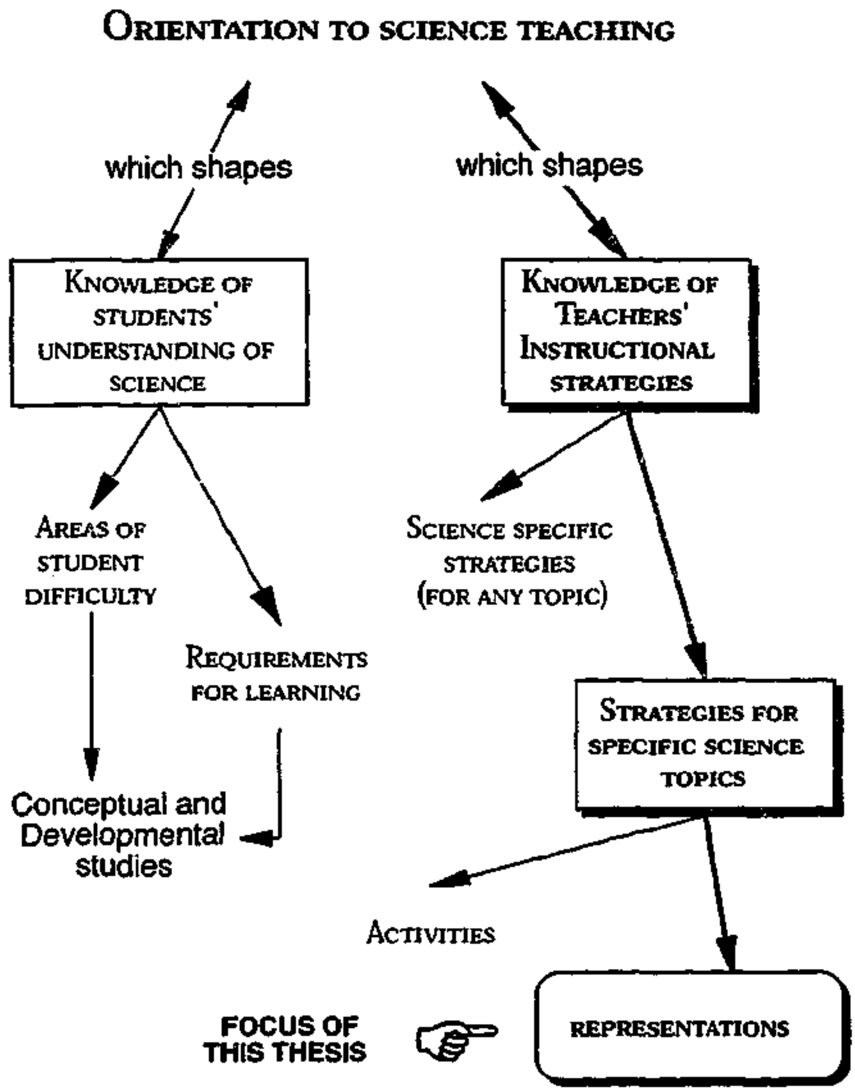
In the context of this thesis, PCK offered a focus for the research because whereas experienced physics teachers can be expected to have developed a robust and tested set of teaching strategies, analogies, examples, and metaphors, i.e., PCK, for use in conveying the subject matter to their students (cf. Niess & Scholz, 1999, p.257; Zembal-Saul et al., 1999, p.242-3), preservice, or beginning teachers may not have developed such a rich range of pedagogic knowledge and skills. This is particularly likely to be so if they have only had a limited opportunity to teach physics in their preservice teacher-education course, and that for that reason, *rather than because of some deficiency in their physics content knowledge*, may be unable to be effective physics teachers (Zembal-Saul et al., 1999, p.243). This seemed to be particularly likely in the case of my preservice teachers.

This thesis explores this proposition in the context of preservice physics teachers' knowledge of the gravity context of the Victorian Certificate of Education physics curriculum. The specific PCK focus of this thesis is the participants' topic-specific PCK (T-PCK) of gravity in the context of the VCE physics unit *Around the Solar System*[12]. Figure 2-1 on page 24 depicts this focus using the model of PCK for

11. see page 15.

science teaching developed by Magnusson, Krajcik, & Borko (1999, p.99) — arguably the best articulated model of PCK for science teaching, and that which has been adopted for this thesis[13].

Figure 2-1: Focus of this thesis on topic-specific PCK and its relationship to conceptual and developmental studies. (adapted from Magnusson et al., 1999, p.99)



In this model, T-PCK is seen as consisting of:

> ...teachers' knowledge of specific strategies that are useful in helping students comprehend specific science concepts. (Magnusson et al., 1999, p.111)

12. see Section A.1 on page 1.
13. as discussed in Section 3.1

This has two components — *activities* and *representations*. Activities are the educational learning activities that are used to help students learn about the content. Representation refers to:

> ...teachers' knowledge of ways to represent specific concepts or principles in order to facilitate student learning, as well as knowledge of the relative strengths and weaknesses of particular representations. (Magnusson et al., 1999, p.111)

as well as:

> ... a teacher's ability to invent representations to aid students in developing understanding of specific concepts or relationships. (Magnusson et al., 1999, p.111)

This thesis examines the participants' verbal 'representations' of gravity through the use of a semi-structured clinical interview that employs a variety of probes — video clips, computer-based simulations, and computer microworlds, in an attempt to gain insights into their T-PCK of gravity as they discussed the events occurring in the probes.

This approach was adopted for two reasons. First, a variety of pragmatic considerations (described later in Section 5.5.1 on page 154) dictated the use of this format over direct classroom observations. Second, the ill-defined nature of PCK and related methodological concerns have led to increased recognition of the need to gather multiple sources of data about PCK in order to gain a more holistic representation of it (e.g., Baxter & Lederman, 1999; Gess-Newsome, 1999; Loughran et al., 2000; Magnusson et al., 1999, p.127; Veal & MaKinster, 1999). The computer-based method employed in this study is, in part, a response to this need by exploring the potential of computer-based methods in eliciting PCK.

2.3 Teacher Competency Issues

Teachers are expected to demonstrate a wide range of competencies and to be competent in their classrooms[14]. In the Australian context, the Finn and Mayer reports marked the formal establishment of competency statements for the Australian education work force (Finn Report, 1992; Mayer, 1992; National Training Board, 1992). The Mayer report proposed a national set of key competency areas for educators and students. These were adopted by State governments, who developed localised competency statements and standards from them. In Victoria, the Standards Council of the Teaching Profession (SCTP) used these to develop a statement of 'Dimensions of Teaching' (SCTP, 1996b) which identified five key areas for the development of competency statements and performance indicators. Before graduate teachers are able to be employed, they are required to have a well developed portfolio as evidence of their competency in each of the five dimensions of teaching:

- Content of teaching and learning
- Teaching practice
- Assessment and reporting of student learning
- Interaction with the school community
- Professional requirements

This framework was used to develop certification requirements for graduating teacher-education students, and for course accreditation requirements for teacher-education providers (SCTP, 1996a).

14. A distinction rooted in Chomsky's (1957) notions of performance versus competence.

As a teacher-educator, I must ensure that my students meet the required standards, and have the necessary competencies for certification as teachers. Of particular relevance to this role is the SCTP dimension of the 'content of teaching and learning'. In the SCTP competency framework, beginning teachers should, with respect to the dimension of 'the content of teaching and learning':

- demonstrate basic knowledge of areas of the Curriculum and Standards Framework and/or Victorian Certificate of Education and school charter goals applicable to their teaching;
- know and apply materials, teaching methods and programs associated with the curriculum area being taught;
- know the characteristics of learners and current educational trends and strategies.

This study is concerned with the first of these — my preservice physics teachers' knowledge of the Victorian Certificate of Education physics course (Board of Studies, 1994; VBOS, 1997). At the end of this study I wanted to be able to understand what their difficulties with teaching physics were — whether they arose from their science content knowledge or aspects of PCK, and to have a knowledge base that would both inform my teaching, and underpin the development of computer software that would be both developmental and diagnostic. (The actual development of such programs falls outside the scope of this thesis).

2.4 The Educational Context

This thesis addresses a serious issue in teacher-education — the need to ensure that science teachers are competent, and are able to clearly and accurately articulate to their students the scientific knowledge that they have (frequently) learnt mathematically and symbolically. The issues here relate to curriculum development and pedagogical change in physics teaching at school and university (e.g., Cortini, 1995; Monk, 1995). Arons (1990, p.17), in discussing the competencies and learning difficulties of physics teachers, comments:

> ... teachers, except for a very small minority, have not developed the necessary knowledge and skills. (Arons, 1990, p.17)

and also that...

> The vast majority of working teachers...will not develop the necessary knowledge and skills spontaneously. They need help, and this help must be forthcoming from the college-university level in both preservice and in-service training. (Arons, 1990, p.15)

This position is at the heart of this work. By providing me with insights into some of the specific problems, possible 'misconceptions'[15] (e.g.Gunstone, 1987; Hestenes, Wells, & Swackhamer, 1992; McCloskey, 1982; Minstrell & diSessa, 1994; Monk, 1995; Roschelle, 1991b; Sequeira & Leite, 1991) and knowledge deficiencies that my preservice teachers have with a range of gravitational concepts, particularly when adopting a contextual teaching approach, I hoped to be better able to help them to overcome them. I anticipated this research providing me with direction for improving my physics methods course in order to help my students be more reflective and metacognitive about their physics teaching difficulties, and also to identify approaches that could be incorporated to assist them in overcoming their difficulties.

15. Used here in the inclusive sense. (cf. Mental Models)

2.5 Social Relevance and Contextual Teaching

As society increasingly employs science and technology in a wide range of roles, people must be able to understand the complex world in which they live, and to be able to be 'in control of the technology', not its servant (cf. Cajas, 1999; Touger, 1993). This is important for both personal and societal reasons. This requires that they understand the application of science to societal issues, and that they have access to ways of analysing the impact of science and technology on society. Failure to address this issue will very likely lead to a technologically uninformed populace unable to make informed decisions about issues of great social and personal concern. Ensuring that teachers are competent to present science in a contextual model, such as the VCE physics course, will help to develop the desired knowledge in the community. The significance of context in science teaching is explored below in the case of gravity, particularly the motion of planets and asteroids, as this is the specific VCE area of study that this thesis examines.

2.5.1 Historical aspects

Humans have consistently shown curiosity about gravitationally influenced events over most of recorded history. In 1998, over one million people added their name to a list that will travel on NASA's StarDust mission to the comet Wild 2 (NASA, 1998b). Phenomena such as the motion of planetary bodies, flight, and free fall appear regularly in the scientific or religious works of many ancient civilisations (Frankfort, Frankfort, Wilson, & Jacobsen, 1964, p27; Neugebauer, 1957, p55). For example, the ancient Babylonians' meticulous recording of astronomical events dating from 747 B.C. demonstrates that they had a strong concern for the motion of heavenly bodies, and were aware of the complexities of the retrograde motion of the planets (Toulmin & Goodfield, 1963, p32). Their detailed data allowed them to predict, but not to explain, the chronological appearances of the planets and eclipses. However even this phenomenological understanding was not available to all; in Babylonian society, the recording, preservation and interpretation of astronomical data was the responsibility of a select priesthood (Toulmin & Goodfield, 1963, p57) and the general populace had neither access to, nor an understanding of, the recorded data, nor its method of interpretation:

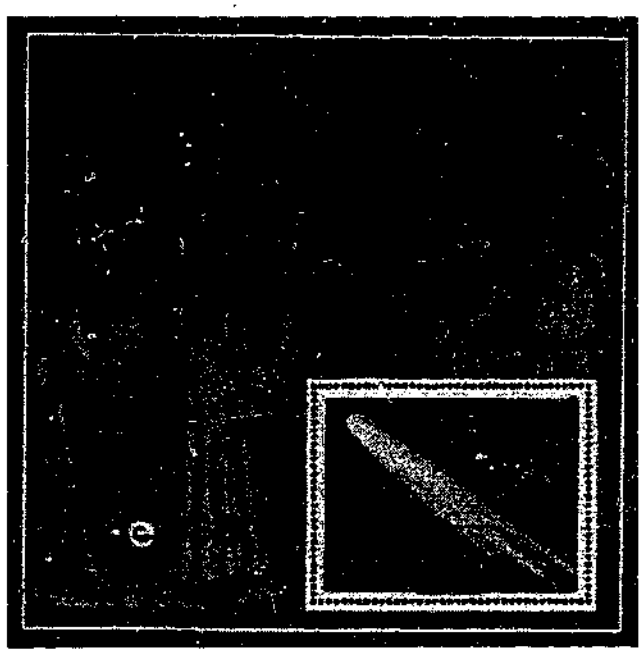
> *One must simply realise that mathematics and astronomy had practically no effect on the realities of life in ancient civilisations.* (Neugebauer, 1957, p71)

The formulation of the general field of mechanics developed out of similar pragmatic concerns about the phenomena of terrestrial motion (Butterfield, 1965; Clagett, 1959). Since the publication of Newton's *Principia* in 1687, scientists have had a clear conceptual model of the basis of mechanical phenomena in normal[16] contexts on Earth (see for example the review by Hurd & Kipling, 1964, p193-208). Similarly, for several centuries, the theories and astronomical observations of Copernicus, Kepler and Newton have provided a clear, if limited, basis for understanding the majority of routinely observable planetary events in the solar system (Hutchins, 1952; Posey, 1988; Strahler, 1965). Irregular events such as the Star of Bethlehem (Allzeit Online, 1999; DeYoung, 1997a, 1997b) and supernovae such as the 'Chinese star' of 1054 (the Crab nebula), 'Tycho's star' of 1572, and 'Kepler's star' of 1604, ensured that heavenly events were occasionally very

16. i.e., non-relativistic motion of objects on Earth and planetary motion.

prominent in the public arena. It would therefore seem reasonable to assume that people should now be better informed about terrestrial mechanics and planetary motion than the ancient Babylonians were (e.g., Cohen, 2000; Galili, 1996, p.233). Comets and meteors featured widely in art, as portents of change or disaster, as for example in Gioto's 'The adoration of the Magi' in 1301, and the Bayeux tapestry of 1066, which were reprinted by many nations on a wide variety of stamps for the 1985-6 return of Halley's comet.

Figure 2-2: Stamps portraying historical art work with comets (inset with Halley's comet and the European Space Agency satellite probe to Halley's comet).



Asteroids and comets were prominent in 18th and 19th century British art and science (Pasachoff & Olson, 1995). Halley's comet of 1910 was readily observed by the public and widely discussed in the media of the time (e.g., Figure 2-3).

Figure 2-3: Halley's comet depicted on a 1910 postcard with images of the 1835 appearance.

The possible origins of the Tunguska impact (Granite Productions Ltd, 1998; Lynne & Tauber, 1995; SKY, 1996) were also widely reported on, and in the 1970's, the Apollo moon missions provided strong visual images of the cratering of the Moon, and the realities of space flight — such as the Apollo 13 incident.

2.5.2 Contemporary aspects

The origins of comet *1993e* (Shoemaker-Levy 9) and the potential effects of its impact with the planet Jupiter in July 1994 were widely discussed in the public media (e.g., Ewing, 1994; McCarthy, 1994; O'Neill, 1994a, 1994b, 1999a, 2000a; Wendt, 1994) and aroused widespread interest in both the public and in scientists (Beatty & Goldman, 1994; Bruton, 1994; Fitzsimmons, Williams, Lagerkvist, &

Dahlgren, 1991; Hahn, 1992; Hills & Goda 1999; Tancredi, Lindgren, & Rickman, 1990; West, 1994). Comet Hale-Bopp was also accorded widespread media publicity because of the mass suicides associated with it (CNN, 1998; Eisenberg, 1997; Kronk, 1997; NASA, 1998a). The 'near miss' of the Earth by asteroid *1997 XF11* in 1998, and again in 1999 by *1999 AN10* and other events (e.g., Matthews, 2001; McCabe, 2000; O'Neill, 1999a, 1999b, 2000a, 2000b; Rees, 2000a, 2000b; Vergano, 2001), have caused consternation in the scientific community, and led to the development of the Torino scale for measuring extra-terrestrial impact damage (Binzel, 2000; Cohen, 1999), the establishment of the Near Earth Orbit observation project (Coster, 2000), the Spacecraft Foundation (Tate, 2000), and the UK's 2000-RD53 defensive astronomy program (Chapman, 2000; Hills & Goda 1999; McCabe, 2000).

Popularised in television series such as The Simpsons (FOX Television, 1995), The World Around Us (McCarey, 1999), and Discovery Profile (Discovery Channel, 2000; Discovery Online, 1999; Taylor, 2000), as well as major films such as *Dinosaur* (Disney, 2000), *Armageddon* (Bruckheimer & Bay, 1998), and *Deep Impact* (Paramount Pictures, 1998), the potential effects of the impact of extra-terrestrial bodies such as *1993e* presumably have made a significant impression on the public psyche (e.g., McCarey, 1999). However, whilst it is likely that, by virtue of their training, many scientists and engineers keenly understood the fundamental gravitational nature of the events on Jupiter, and many of the details in films, there is little evidence, if any, to suggest that these sophisticated understandings were widely shared by the general populace, and particularly not by school-aged children. For example, in both Armageddon and Deep Impact, nuclear explosions were used to fragment the asteroids — a scientifically dubious proposition at best (Jian Shi & Min, 1997; Shubin, Nechai, Nogin, Petrov, & Simonenko, 1997; Taylor, 2000). These films gave the impression that the collision of the major fragments would still occur, essentially unimpeded, unless they were shattered into small fragments that would burn up in the Earth's atmosphere — a 'centre of mass' argument that gave little regard to the motion of the (presumably) radially expanding fragments.

2.5.3 Public understanding of science

There is ample evidence to show that even the intensely personal experience of daily life in the Earth's gravitational field is not interpreted by the majority of people in the same way as by scientists (Mali & Howe, 1979; McCloskey, 1982, 1983b; Noce, 1982; Smith & Treagust, 1988), a view that has significant importance for schools in teaching 'science' and in developing a 'socially-responsible' science curriculum (e.g., Cajas, 1999; Cross, 1999; Cross & Price, 1999; De Vos & Reiding, 1999; Fensham & Harlem, 1999; Jenkins, 1999). Such gaps in knowledge and understanding between 'scientists' and 'the public' exist across most areas of scientific learning (e.g., Editorial Board, 1985). Etzioni (1974) refers to this phenomenon as 'the public understanding of science' (cf. Durant, Evans, & Thomas, 1989; Jefferson Physical Laboratory, 1974). As well as causing concern to classroom teachers, this epistemological divide is also a potential societal concern, particularly in emerging technological societies where there is a prima-facie link between the economic well being of the society and the level of technological and scientific literacy of the work force:

> Everyone needs some understanding of science, its accomplishments and its limitations, whether or not they are themselves scientists or engineers. Improving that understanding is not a luxury; it is a vital investment in the future well being of our society. (The Royal Society, 1985)

This is in significant contrast to the situation of the ancient Babylonians, where society could leave such specialised knowledge in the hands of a select priesthood, and represents a transfer of knowledge to the populace in response to the need to engage in a technological society.

Formal instruction in 'traditional' science does not necessarily increase scientific literacy — nor can it guarantee increased formal understanding of scientific concepts. Indeed, the work described in this thesis is based on just that proposition. For example, Gunstone's (1987) large-scale survey of 5,500 end-of-high-school students revealed a considerable diversity and uncertainty about many mechanics concepts. His results demonstrate that a population that has formally studied physics can hold a diversity of personal understandings and idiosyncratic interpretations of physical phenomena. If this is true for students who have formally studied physics, it is also highly likely to be true for those who have not. I conjecture, therefore, that the majority of people who paid attention to the events on Jupiter saw them through the same kind of phenomenological frameworks as the ancient Babylonians because, apart from being better informed about the phenomena, they lacked any clear understanding of its scientific, conceptual basis (cf. Acker & Pecker, 1988; Baxter, 1989).

The "Science for All" (Fensham, 1985; Hodson & Reid, 1988; Reid & Hodson, 1987) and "Science-Technology-Society" (Bybee, 1987; Yager, 1993; Zoller, 1992) curriculum movements developed in recognition, at least in part, of the existence of this alternative set of understandings, and the realisation that formal science education was not appropriate for the majority of students who would not undertake tertiary science studies (cf. Leavis, 1962; Snow, 1963; Stinner, 1989, p.19).

These curriculum movements were partly an attempt to return science education to the public arena, but also represented endeavours to popularise and justify the existence of science and technology per se, and particularly to defend, contextualise and update the content (Bybee & Mau, 1986), process (Brunkhorst & Yager, 1986; Bugliarello, 1988) and purpose of science education in the curriculum (Aikenhead, 1992; Bybee, 1987; De Vore, 1992; Fensham, 1988; Hofstein, 1988; Yager, 1993; Zoller, 1992). In addition these movements have acted to define the importance of science in a social and cultural sense, and to defend it against increasing criticisms of social irresponsibility (Bybee, 1979; Bybee, Harms, Ward, & Yager, 1980; Donnelly, 1986; Firnberg, 1979). A post-modern perspective on these programs might suggest that their essential purpose was simply to make science and technology as obviously relevant to modern mankind as astronomy was to the ancient Babylonians!

The roots of the underpinning 'crisis of science education' of the 1980's that generated these changes was that science education had not met the challenge of providing students with the skills for life in a world increasingly influenced by science and technology, and helping them to understand their responsibilities in it (e.g., Aparo, 1995; Bird, 1977; Hilborn, 1977; Holton, 1993, 1996; Hurd, 1984;

Layman, 1983; McDermott, 1990; National Science Foundation, 1996; Rowe, 1980a, 1980b; Schmitt, 1994; Science Council of Canada, 1984; Tobias, 1992; Wolf, 1994).

2.5.4 Curriculum considerations

In Victoria, after protracted local and national discussions, these issues helped to inform the development of a contextual physics curriculum that focused on describing and explaining 'real world' physics, and issues in science and technology, as a pathway to more formal physics studies at university (AEC, 1990; Armitage, 1990; Board of Studies, 1994; Commonwealth Schools Commission, 1987; Ministry of Education, 1985, 1987; Powe, 1990). A primary aim was to make physics more relevant to the average school student and citizen:

> It is also part of the human condition to use knowledge to gain control. Knowledge of physics has led to developments in technology, some of which (for example, radio communication and electrical appliances) have had a profound impact on social structures. The social effects of such technologies may be either positive or negative and, as has been the case in nuclear science, the use to which the knowledge is put may itself direct the course which physics takes. (Board of Studies, 1994, p7)

Of equal importance was to provide a basic scientific literacy with which to help citizens to understand scientific developments and events in their society...

> At an even more subtle level of interaction, some developments in physics, such as the Copernican revolution, Galileo's confrontation with the Church and challenges to accepted ideas about the predictability from quantum mechanics, have helped to shape society's collective consciousness. Aspects of the theory of relativity, for example, have passed into modern folklore. (Board of Studies, 1994, p7)

This course replaced an 'elitist, male-oriented and sexist' academic physics study that had previously attracted a small number of mainly male students (Di Pilla, 1996; Dunbar, 1990; Healy, 1989; Hildebrand, 1996a, 1996b; Wyatt, Whitehead, & Hart, 1996). Subsequently, enrolments in school physics increased enormously, with a high female participation rate (Hildebrand, 1996b).

This was the course, and context, that my students were expected to be able to teach. It requires a strong knowledge of physics, and a good understanding of a wide range of contextual issues. In Unit 4 of the VCE physics course, there is the potential to make use of the movies, publications and on-line resources of, for example, NASA (e.g. NASA, 1998a) to make an interesting, stimulating, and challenging curriculum that would both inform the students about the underlying physics, and also provide the personal and social outcomes described above. At this time, I do not believe that my students can do this, and therefore, are perhaps not making a significant contribution to the scientific literacy of their students, especially in regard to understanding real-world contexts and issues.

By assisting them to have a better conceptual understanding of the relevant physics in context, and of the learning difficulties confronting physics learners, and of their own difficulties in teaching, my students should become more accurate (in terms of the physics concepts) and more effective communicators. In Shulman's terms, by developing their pedagogical content knowledge, they will be more competent and effective teachers. Hopefully they will be able to teach the VCE physics course — both content and context, and hence make a contribution to increasing the scientific literacy of their students; an important personal and national development.

2.6 Research Questions

In order to discover what the students' understandings of gravity, and the nature of their difficulties in teaching it were, this study explores their thoughts with a series of computer simulations, responses to video clips, and data collected from a diagnostic questionnaire — the Hestenes Force Concept Inventory (FCI) (Hestenes et al., 1992), all collected during a semi-structured interview. The video clips employed in the study were segments of cartoons that demonstrated many of the aspects of 'cartoon physics' that are in direct contradiction to Newtonian physics (Kimler, 1998; Polos, 1995; Toon-D Productions, 1997). These were used as 'discrepant events' (Bliss, 1989; Driver, Guesne, & Tiberghien, 1989a; Fensham & Kass, 1988; Jonassen, 1995) to probe the students' knowledge of Newtonian physics by having them choose between a cartoon physics explanation and a Newtonian alternative (cf. Sproull, 1991). The FCI also forces students to choose between Newtonian and 'common sense' alternatives across a range of force-related contexts and concepts. The computer simulations focused on particular aspects of the VCE Unit 4 syllabus that forms the focus of the study. Student responses to the computer simulations and video clips were audio taped and videotaped for subsequent analysis.

Knowledge of the students' personal context — the preservice science teacher-education course at Deakin University, is important in understanding how it has shaped this research. Therefore a description of the course as it was when the research was conducted (1995-1997) is given below.

2.6.1 The context

The students in my study were drawn from the Bachelor of Education – Secondary (BES) on the Rusden campus of Deakin University. This four-year degree concurrently develops both the students' content knowledge in their selected fields, and their teacher education knowledge, skills, and competencies. All had selected physics as one of their teaching subjects, though *none* had undertaken it as a 'major' academic study. The BES is a combined four-year degree. Part of the course was conducted by the Faculty of Applied Science, which taught the academic components — physics, mathematics etc. The Faculty of Education taught the 'professional' components of the course, consisting of teaching methodologies (of which physics was one), practicum, and general education subjects.

Students were required to have at least two specialist teaching methods, which normally related to a major and sub-major study within the Faculty of Applied Science, the pre-requisite for entry being a minimum of a three-year sequence of study in an area. A 'full' major study consisted of a four-year sequence of units in some subjects (such as Mathematics) and three in others (such as Physics), although specialist fourth-year units could be undertaken in Physics and some other sciences. However, because a diverse range of teaching subjects were offered in the BES — the most popular courses being Art, Biology, Chemistry, Computer Studies, Drama, Economics, English as a Second Language, Geography, History, Language, Legal Studies, Mathematics, Media, and Physics, many students undertake their second specialism in another Faculty. In many cases science forms the sub-major component of their course. Such students would have only formally studied science — one strand such as chemistry or physics, for three years at University level. In the BES, this was equivalent to approximately 30%-35% of their course for each of the three years. A major study in one science area would have entailed that same level of commitment for each of the four years of the course.

The science-education 'methods' common core course was a semester-long unit of three hours per week that focused on the years 7-10 science curriculum. The following semester, students undertook two or three specialist subjects, such as physics, chemistry or biology (each one hour per week for the semester) that focused mainly on the senior school VCE curriculum. The majority of students undertook one elective study outside of their academic areas in order to increase their range of teaching offerings, and hence their chances of gaining employment.

The science core was based on a 'constructivist' model developed loosely from notions emanating from children's science (e.g., Driver, Guesne, & Tiberghien, 1989b), and the PEEL project[17] (e.g., Baird & Northfield, 1992; Gunstone & Northfield, 1994), in which appropriate pedagogy was modelled by the staff. Some sessions were conducted in school classrooms with the preservice teachers being responsible for teaching small groups of children. Other sessions developed curriculum models and materials, and provided for reflection on their teaching sessions. The VCE method units focused heavily on the curriculum requirements of the VCE, tips on good teaching strategies, and the specifics of assessment policies and processes.

2.6.2 The research participants

The participants in this research consisted of three cohorts of fourth-year undergraduate university students undertaking my physics methodology course during 1995, 1996, or 1997. All were taking physics as a sub-major study in their academic course, and as a second teaching method in their education studies —

17. Project to Enhance and Extend the quality of Learning.

none had majored in physics. For each cohort, in the first session of each course I described the course outline and the nature of the research to be undertaken, its fit with the course, and the methodology to be employed. Participation in the research was to be purely voluntary as a Deakin University condition of granting permission to conduct the research was that it was to take the form of a voluntary extra-curricular activity for the students. In each cohort, four or five students volunteered for the research project. In accordance with both Monash and Deakin Universities' requirements, the students were informed that they could withdraw from the study at any time, for any reason, without having to provide an explanation. Of the thirteen students who volunteered over the three years, only two students withdrew from the study; one moved interstate and withdrew from the BES, and the other withdrew left to take up a position in industry. Table 2-2 lists the details of the preservice teachers who participated in the study.

Table 2-2: Basic details of the participants in this study

Student (pseudonym)	**Method subject combinations**	**Gender**
Joanna	Mathematics, Mathematics & Physics	F
Susan	English, Mathematics & Physics	F
Denise	Mathematics, Mathematics & Physics	F
Alex	Mathematics, Mathematics & Physics	F
Jim	Biology, Mathematics & Physics	M
Joe	Biology, Mathematics & Physics	M
James	Sociology, Biology & Physics	M
Steve	Physical Education, Physical Education & Physics	M
Alan	Chemistry, Mathematics & Physics	M
Anne	English, English & Physics	F
Helen	Drama, Mathematics & Physics	F

2.6.3 The questions

This thesis addresses two specific questions:

1. What is the nature of the participants' T-PCK and content knowledge of gravity in the selected VCE context?
2. What is the nature of a pedagogical knowledge-base that could inform the development of software that could be constructed to support and facilitate the development of both T-PCK and content knowledge in this area of the VCE curriculum?

The first question is in two parts. First, their conceptual knowledge is examined through the FCI and a semi-structured interview. The data form a 'snapshot' of each of the participant's knowledge of gravity within the VCE context. These snapshots are examined by means of a content analysis in an attempt to identify the state of the individual participant's physics content knowledge. Second, their pedagogical content knowledge was examined by searching for evidence of elements of T-PCK by means of examining the language that was used by participants in their responses to the probes employed in the interview.

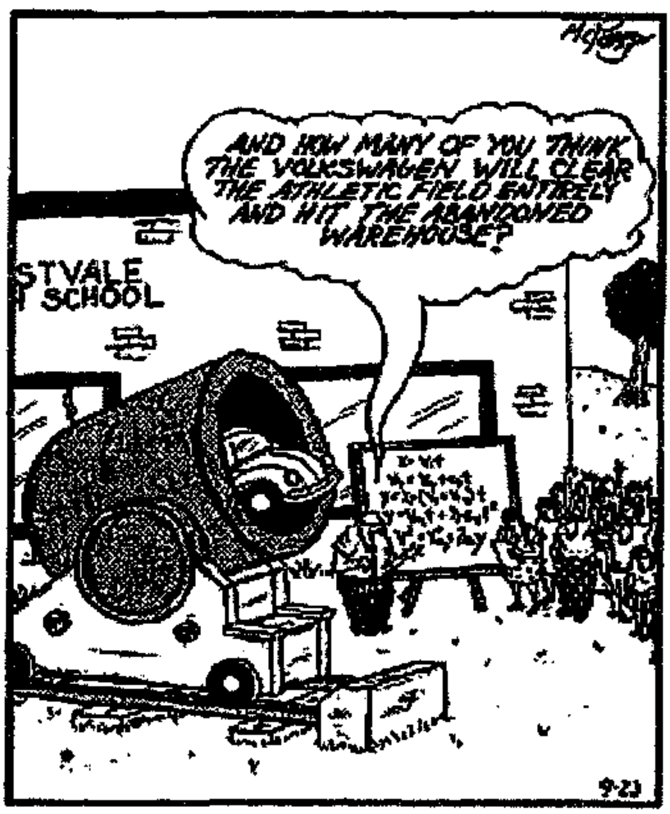
Question two was addressed by a reflective examination of the results of the above analyses, leading to the development of a conceptual software design for 'PCK-enhanced' software for learning physics (i.e., specifically the content area relevant to the VCE context described previously). As discussed elsewhere (see page 135), the development and trialing of this design did not form part of this thesis because of structural and course changes in the University arising from its amalgamation with Victoria College.

2.7 Chapter Review

In this chapter, the origins of the research were described, and located within both the science-education literature, and the wider literature on teacher competency — being framed by Shulman's models of PCK. The significance of the study was articulated for both educational relevance, and social relevance to the wider community. The nature of the research conducted for this thesis was outlined through a description of the context, participants, and the research questions.

Chapter 3

Pedagogical Content Knowledge



Thanks to the innovative labs of teacher Herb Krenley, physics quickly became Westvale High's most popular course.

3

Pedagogical Content Knowledge

> Although PCK creates a home for the "unique" knowledge held by teachers (Shulman, 1987, p. 8), identifying instances of PCK is not an easy task.
>
> (Gess-Newsome, 1999, p.10)

3.1 Teaching and knowing physics

The essence of this thesis is about the dichotomy between 'knowing' physics — in the formal sense of understanding concepts and laws (and being able to use that knowledge to solve problems), and being able to teach it effectively, because the two are not necessarily synonymous (e.g., Arons, 1995, p.2; Magnusson et al., 1999, p.112; Yager, Hidayat, & Penick, 1988; Zembal-Saul et al., 1999, p.242-3) — exactly the point made by the previous description of the preservice teachers' problems in teaching about gravity (cf. Tobin, Tippins, & Gallard, 1994, p.66).

> ...a strong content knowledge of science has little relationship to a person's understanding of science and his or her ability to communicate this understanding. (Yager et al., 1988, p.174)

However, a strong subject matter understanding is an essential component of effective science teaching (Zembal-Saul et al., 1999, p.243). Cochran and Jones (1998, p.711) note that preservice teachers commonly showed little integration or stability in their subject matter knowledge[1], and were unable to make links between

1. see Cochran and Jones (1998) p.707-717 for a more extensive discussion of this issue.

their subject matter knowledge and pedagogy because of a lack of deep understanding of content and context (e.g., Ball & McDiarmid, 1990; Tamir, 1992). Bischoff, Hatch, and Watford (1999) raise similar concerns about preservice science and mathematics teachers' competence in lesson planning and subject matter knowledge, with only 10% of those studied being capable of demonstrating competence at the required level. Their lesson planning contained numerous content errors, and was predicated on a genre of teaching which was based on algorithmic learning, rote memorization, and procedural knowledge. Bischoff et. al. (1999) call for a greater synthesis of content and pedagogy in a learning environment that is developed around contemporary theories of learning.

It is helpful to have a theoretical framework of teaching that encompasses this view in order to have a structure to guide the research, and to be able to relate the research findings to its literature base. The notion of 'knowledge bases for teaching' is one such framework that is relevant to this study (e.g., Grossman, 1990; Shulman, 1987). This is a large, and arguably vague notion to which the Goldilock's principle (Katz & Raths, 1985) can be applied, meaning that it needs to be further refined and articulated before being useful to researchers and practitioners. In cognisance of this, in examining the preservice teachers' understandings I have adopted the essential aspects of Shulman's PCK, one of seven categories of 'teacher knowledge' identified by Shulman (Gess-Newsome & Lederman, 1999; Shulman, 1986a, 1986b, 1987; Shulman & Tamir, 1973; Wilson, Shulman, & Richert, 1987). This is a theoretical model within the 'knowledge base for teaching' framework that historically has been poorly represented in the field of teacher education research (Carlsen, 1999; Shulman, 1983, 1984, 1986a).

> As teacher educators we must consider how best to introduce this knowledge into programs of teacher education. (Grossman et al., 1989, p.24)

PCK provides a structure with which to engage with the notion of knowledge bases for teaching. Anderson and Mitchner (1994, p.6) describe it as providing an enhanced view of the academic orientation of research into science-teacher education. Shulman's model is not a rigid empirical model for the study of teaching, but rather, a framework for considering teaching — a position resonant with Hirst's view of the role of theoretical positions in the field of educational research:

> ...the place of theory is totally different (*from the scientific view*). It is not the end product of the pursuit, but is rather constructed to determine and guide the activity. (Hirst, 1971, p.342) (emphasis added).

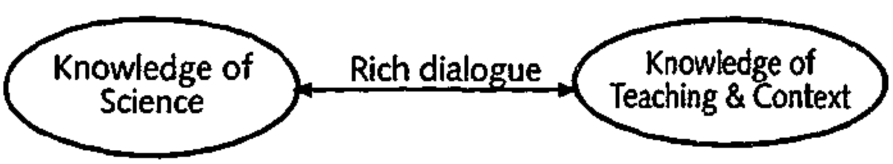
Shulman acknowledges the utilitarian (as opposed to theoretical) nature of PCK:

> Every educational idea is inherently incomplete and probably seriously flawed. An idea is useful to the extent that it can stimulate the thinking and scholarship of others. I trust our work on pedagogical content knowledge may meet those standards of utility. (Shulman, 1999, p.xi)

PCK differs from formal 'subject content knowledge' — the recognised facts of the field, logical relationships among facts, concepts, and principles, as well as its substantive and syntactic structures, and associated logic framework and paradigms (McEwan & Bull 1991, p319; Parker & Heywood, 2000; Schwab, 1978). It has a focus on practitioner dimensions such as '...ways of representing the subject to make it comprehensible to others.' (Shulman, 1986b, p.9) This is the essential basic competency in the SCTP dimension of 'the content of teaching' that this study addresses. PCK is now seen as an essential component of the knowledge base of science teaching (e.g., NSTA, 1999), and the area that is likely to have the most impact on teachers' classroom actions (Gess-Newsome, 1999, p.4).

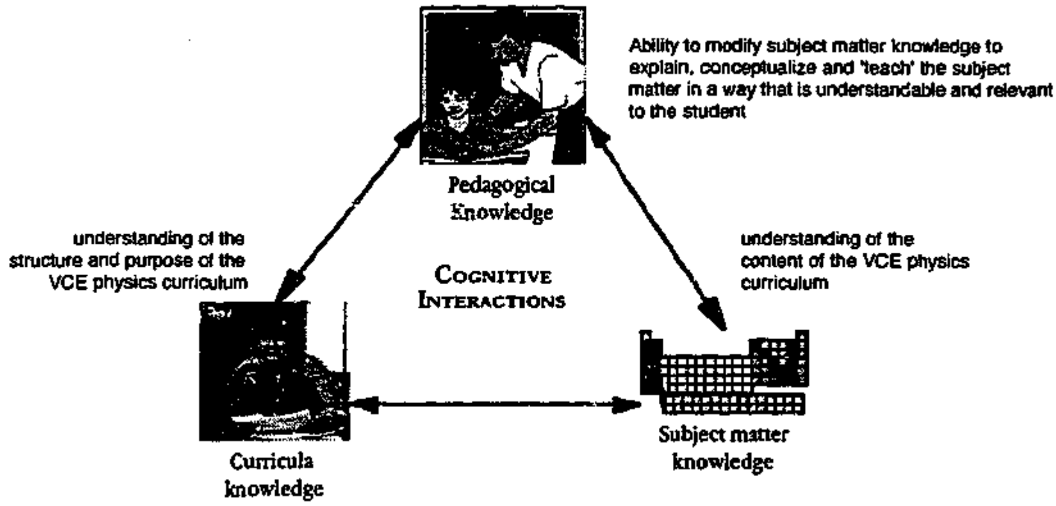
Shulman's model is based on the proposition that content knowledge (e.g., of physics), such as that gained in undergraduate courses for example, does not provide an adequate preparation for teaching: that learning more science, or knowing it 'better' does not necessarily produce a better science teacher. In a very general sense it perhaps provides a rationale for the apocryphal 'I didn't know this material until I had to teach it'. Giannetto et. al. (1992, p.360) note that '...in the literature, very little attention has been given to possible discrepancies between codified science and teachers' science'. Figure 3-1 portrays the basic relationship underpinning Shulman's model — the need for a teacher to both understand current discourses about (in this study) the nature and content of science, and also to be able to generate (in their teaching) a rich, contextually relevant, and flexible dialogue with their students that makes this comprehensible to them at their current stage of development.

Figure 3-1: The basic relationship between domain knowledge (content) and teacher knowledge underpinning Shulman's model in the context of science education.



Teachers need to have both a well developed understanding of scientific knowledge, as well as a highly developed teaching repertoire that is cognisant of the former: to 'understand what makes a topic in a particular subject discipline easy or difficult, the preconceptions and misconceptions that students have, and the strategies for dealing with them.' (Tsui, Coniam, Sengupta, & Wu, 1995) Shulman's initial conception of teacher knowledge identified three essential categories (knowledge bases) as in Figure 3-2 (Shulman, 1986a, p.26). This develops the relationship depicted in Figure 3-1, but with the 'Knowledge of teaching and context' being split into two categories — 'pedagogical knowledge' and 'curricular knowledge'. The former includes the T-PCK that is the focus of this study.

Figure 3-2: Shulman's original 'pedagogic content knowledge' model (after Shulman, 1986b).



Shulman's third original category is curricular knowledge, which refers to the knowledge of the program and the materials that have been designed for the teaching of a particular topic at a particular level. Carlsen's mapping (1999, p.137) of changes in the nature of key knowledge domains for teaching (Table 3-1) shows that while their focus and nature has varied over time, PCK remains an essential component.

Similarly, the use and nature of the term 'Pedagogic Content Knowledge' has changed since first proposed, reflecting increased understandings of the complexities of teaching (Anderson & Mitchner, 1994, p.17; Cochran et al., 1991; Grossman et al., 1989; Loughran et al., 2000, p.3; Tom, 1992; Wilson, 1991; Wilson et al., 1987), whether or not it was viewed as an attribute of an individual or group (e.g., Loughran et al., 2000, p.4), and where the boundaries between the different knowledge domains were believed to be (the so-called 'boundary' problem). For example, Grossman (1990, p.5) developed a similar model (Table 3-1) by incorporating wider views of teacher knowledge that suggested the restructuring of Shulman's model. Grossman's model of PCK also interacts dynamically with its components. In the context of this study, Grossman's model offers no particular advantage over Shulman's.

Table 3-1: Selected domains of teacher knowledge (Carlsen, 1999,p.137).

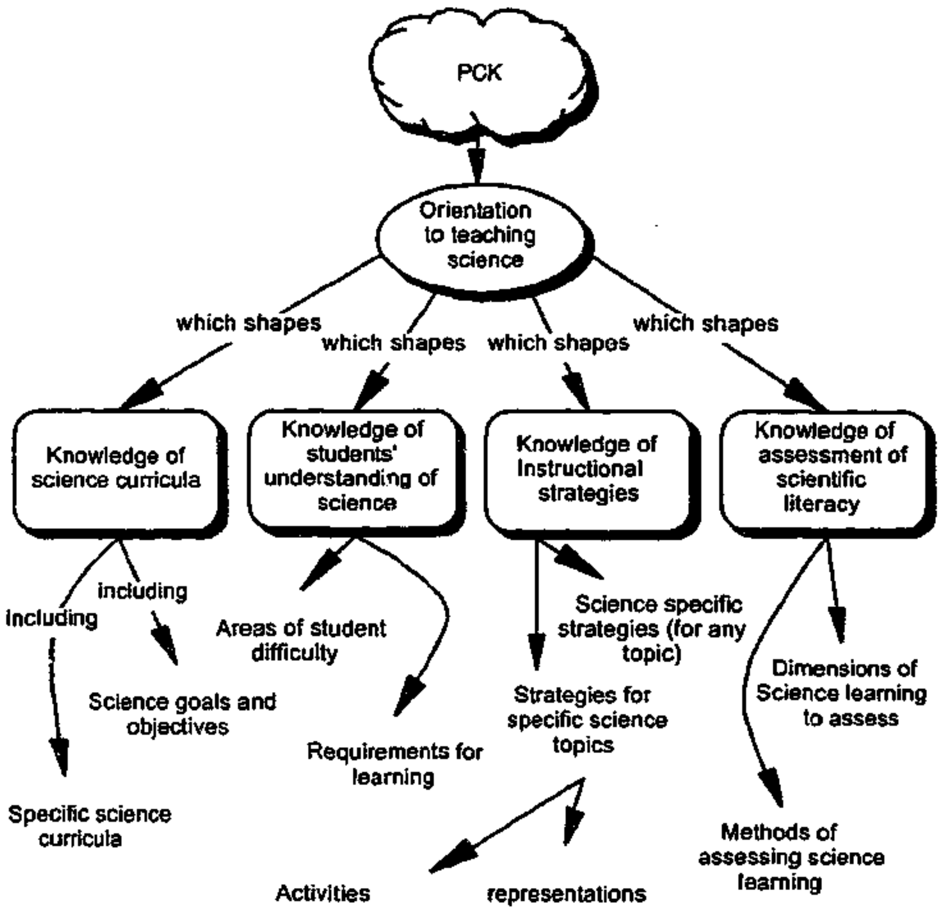
Knowledge category or domain	Shulman, 1986c	Shulman, Sykes & Phillips, 1986	Shulman, 1987	Grossman, 1990
Curriculum	Subsidiary category	Major category	Major category	Subsidiary category
Learners and learning	Not explicitly in model	Major category	Major category	Subsidiary category
Liberal knowledge and skills	Not explicitly in model	Major category	Not explicitly in model	Not explicitly in model
Pedagogy (general)	Not explicitly in model	Major category	Major category	Major category
Pedagogical content knowledge	Subsidiary category	Major category	Major category	Major category
Performance skills	Not explicitly in model	Major category	Not explicitly in model	Not explicitly in model
Philosophy, goals, objectives	Not explicitly in model	Major category	Major category	Subsidiary category
School contexts	Not explicitly in model	Not explicitly in model	Major category	Major category
Subject matter (content)	Major category	Major category	Major category	Major category
Substantive discipline structures	Subsidiary category	Not explicitly in model	Not explicitly in model	Subsidiary category
Syntactic discipline structures	Subsidiary category	Not explicitly in model	Not explicitly in model	Subsidiary category

Key to table:

MAJOR CATEGORY	SUBSIDIARY CATEGORY	NOT EXPLICITLY IN MODEL
(black)	(grey)	(white)

The diffuse and changing conceptions of PCK make it difficult to define it in ways which are useful in research programs, and lead to a range of interpretations that confound comparisons between studies (e.g., Loughran et al., 2000, p.2). Figure 3-3 depicts a model of the major components of PCK of relevance to science teachers.

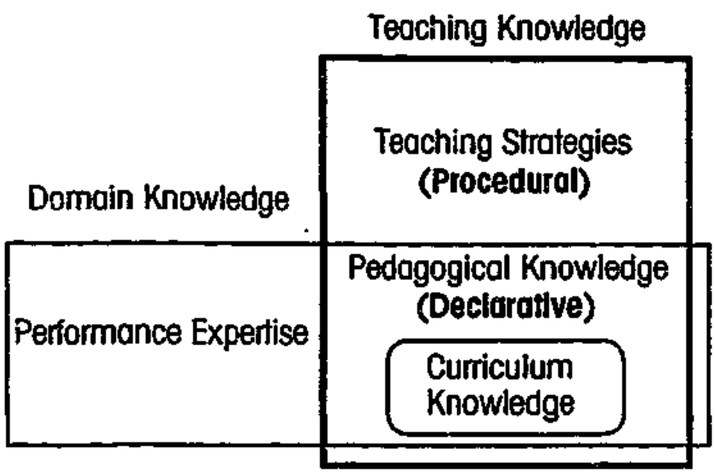
Figure 3-3: Components of PCK for science teaching (Magnusson et al., 1999, p.99)



The model indicates the wide range and diverse nature of the elements of PCK in science teaching, and also suggests that the lack of (other) such specific models or frameworks of PCK is at the heart of the problem of identifying PCK. In comparison, the science content domain has long had the benefit of defined (if changing) conceptual models on which to base a research program in science teaching and learning.

Murray (1996, p. 235-6), arguing from a cognitive science perspective, suggests an alternative structure based on knowledge and process. In Murray's model, 'pedagogical knowledge' is a form of declarative knowledge, and 'procedural knowledge' is process knowledge — e.g., teaching strategies (see Figure 3-4).

Figure 3-4: Murray's pedagogical-knowledge model (Murray, 1996, p.236)



This structure simplifies the development of Intelligent Tutoring Systems (ITS) by providing a first-level functional decomposition of the knowledge base for teaching a particular topic (e.g., Murray, 1996). This is critical to the success of ITS program designers who attempt to recreate expert knowledge in adaptive software environments that require precisely articulated knowledge structures at their core (cf. Goodyear & Tait, 1991; Murray & Woolf, 1992). In this structuralist representation, incorrect or undeveloped knowledge or 'misconceptions' are referred to as 'buggy knowledge' (Murray, 1996, p.237) because they introduce 'errors' into the self-consistent data model that commonly underpins such software.

McEwan and Bull (1991, p331-4), however, argue that all knowledge is pedagogic; that teaching and scholarship are connected through a common purpose — the communication of ideas, and not divided in any formal way. Similarly, Wittgenstein (1958; 1961) shows that even in its simplest forms, language develops in context, and adopts the purposes of its developers. Language (expressing the knowledge it encodes) therefore cannot be separated from the needs of its creators, suggesting that the academic-pedagogic language (and knowledge) dichotomy is perhaps more one of audience dimension or purpose, rather than of substance.

Putnam and Borko (2000, p.5) raise the importance of enculturation into various discourse communities' ways of thinking and dispositions as an essential part of learning, an aspect developed by Loughran et. al. (2000), who argue that PCK might best be viewed as a construct of the discourse community of teachers, rather than as an attribute of an individual teacher. From a different perspective, Keil (1989, p.37) notes that in the case of *nominal-kind* constructs such as PCK (see, for example, Boyd, 1979; Schwartz, 1978, 1980, 1977), their nominal 'essences'[2] (Locke, 1964) '...*reflect little that is intrinsic about the kind, but would instead reflect the intentions of the language users*...', thus adding support for a community basis to PCK[3]. Adopting a post-structuralist stance, Carlsen (1999, p.139) argues that 'In Focaultian terms, "truth" is embedded in a discourse community and is inseparable from that community.' Anderson et. al. (2000; 1996; 1997) also note that situative perspectives on cognition are important in understanding an individual's social and cognitive practices (such as teaching), providing further support for a social or situative view of the nature of PCK. Loughran et al. (2000) develop the significance of language further, suggesting that PCK is in fact an essential part of the professional language of teachers, and argue that a profession must have a 'language' originating in it, and that it is an attribute of the group[4] rather than of any one individual (J. Loughran, personal communication, March 23, 2000). In many ways this is similar to 'distributed knowledge' in which knowledge is an attribute

2. an historical, but useful, perspective for thinking about issues around nominal kinds.
3. but not identifying whether those 'users' are teachers, or are academics theorizing about PCK.
4. i.e., of teachers.

of a group, not of any particular individual (cf. Brown et al., 1993; Brown, Collins, & Duguid, 1989; Putnam & Borko, 2000, p.5; Salomon, 1993), and Resnick's distributed constructionism (Resnick, 1996). In their[5] model, the temporal and contextual instances of attributes of PCK that can be identified in any given teacher at a particular point of time constitute a 'PaP-eR' — an instance (representation) of their Pedagogical and Professional-experience Repertoire. These are contextually and temporally bound, and based in a specific content area (cf. Veal's T-PCK). The significance of this model is that 'PaP-eRs' provide a critical link between the classroom practice of individual teachers, and the professional practice of the teaching community, and that if it were possible to collect a large number of PaP-eRs, the collection would provide strong insights into the true dimensions and nature of PCK. The model also offers the potential to document teachers' changing practices by analysing their use of different PaP-eRs over time and context. Whether this potential can be realised in practice has yet to be tested.

However, PCK and scientific content knowledge are not seen as isolated entities, but rather as intrinsically inter-linked. While to some extent this is simply semantics, there is a deeper justification. In cognitive science models of cognition, such as those underpinning diSessa's 'P-prims' (diSessa, 1985a, 1988, 1993b) and Lawler's 'microviews' (Lawler, 1979, 1984, 1985), knowledge encoded in a mental model may be represented as 'data' and the 'methods' that operate on it. Thus the acquisition of PCK is simply, in Lawler's terms, the development of the methods used to operate on the data (content knowledge) for teaching purposes — the two

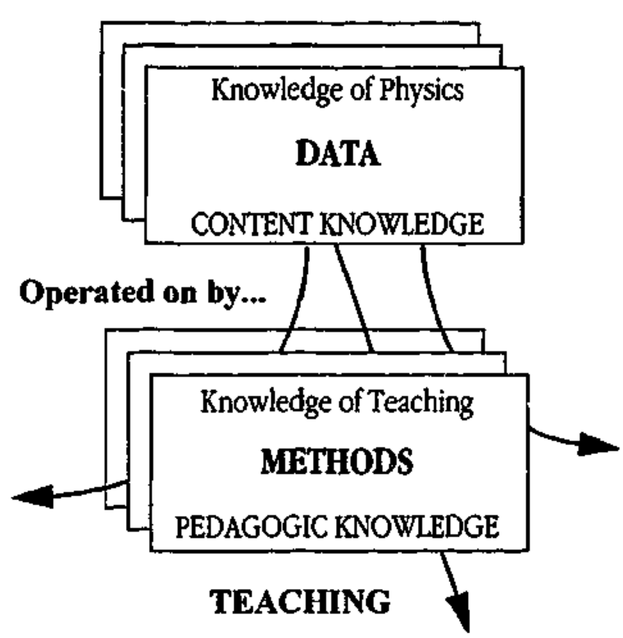
5. i.e., Loughran et. al. (2000).

cannot be separated. Carley and Palmquist (1992) note that the assumptions that underpin this view of mental models are that:

1. Mental models are internal representations.
2. Language is the key to understanding mental models; i.e. they are linguistically mediated.
3. Mental models can be represented as networks of concepts.
4. The meanings for the concepts are embedded in their relationships to other concepts.
5. The social meaning of concepts is derived from the intersection of different individuals' mental models.

Figure 3-5 represents Shulman's model in an information processing format based on Lawler's microview model. The methods portion signifies that teachers' conceptual knowledge of science (i.e, the teacher's data — content knowledge) is acted on by a particular method whenever it is used in teaching, in order to customise it for a particular audience.

Figure 3-5: Shulman's model represented in an 'information-processing' format.



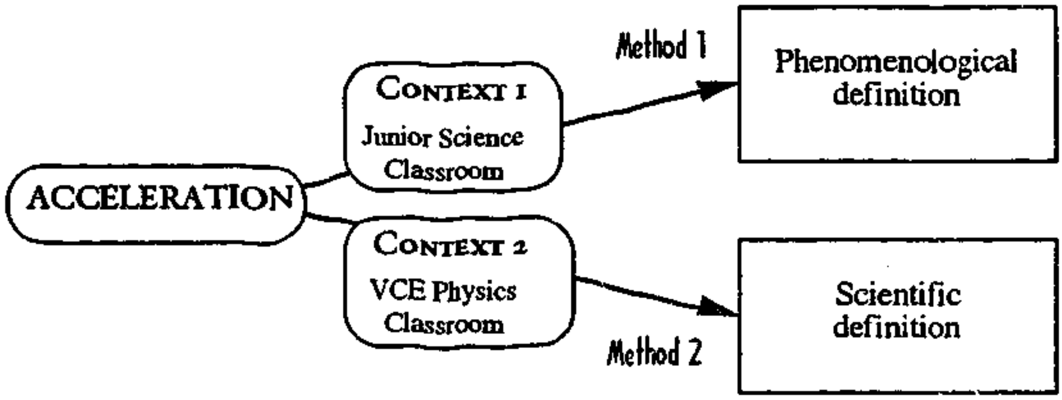
There can be many different methods that operate on specific data, which is consistent with the view that PaP-eRs document one particular temporal instance of some attributes of PCK within a particular context, and that repeated observations of teaching would identify a number of related, but different, PaP-eRs (cf. Figure 3-5). This notion suggests that attempting classroom observations of PCK is a lot like viewing a hologram — an intangible, yet tantalizingly real construct, where what you see depends on how you illuminate it, and where you observe it from (cf. Baxter & Lederman, 1999, p.148; Loughran et al., 2000, p.5). Perhaps this is because while PCK is a well understood abstract academic construct, it is not well understood by teachers because it has not been made 'real'[6] for them, and so it is very difficult for them to articulate its components. The dearth of examples of, at least, T-PCK is perhaps a result of this.

With PCK, what is 'observed' in the classroom at any given time is a particular instance of some attributes of PCK that are temporally and contextually bound, and dependent on the observer's ability to recognise them. These methods can be closely related, independent, or hierarchically related, highly specialised, and contextualised. In teaching physics, for example, there may be many methods that operate on a specific data item such as a component of knowledge about Newton's first law, or gravity, each resulting in a different explanation or approach to teaching in different contexts and classroom situations. Thus the content of science becomes adapted and modified to different classroom and learner realities. For example, in discussing the concept of acceleration in junior science classrooms, it is commonly described initially in phenomenological terms as a change in speed, only later, and perhaps not until a later year level, to be redefined more precisely as the rate of change of velocity when the students have acquired these further concepts. The teacher (presumably) has simplified and contextualised the definition to a point

6. i.e., operationalized so as to be useful in the classroom.

where it is in fact scientifically incorrect, but which is deemed appropriate for the students current level of understanding. This can be viewed as having (at least) two methods to deal with the concept of acceleration; which one is used at a particular time will depend on the context in which it is being used. The scenario depicted in Figure 3-6 is a coarse example, in that there are large differences between the contexts and methods that relate to them. The underpinning model, however, can equally and easily accommodate much more closely related contexts and methods (as utilised in this study), and is not inconsistent with the PaP-eR model.

Figure 3-6: An example of the relationship between methods and context.



3.1.1 Significance of Lawler's model

In diSessa's model, observation and experience leads to the generation of the phenomenological primitives (P-prims) such as 'rocks fall' or 'feathers float', that form the foundation of the observer's knowledge, which is then interpreted, or 'perceived' by the observer (diSessa, 1983, 1988, 1989, 1993b). However, perception is not knowledge[7], and the antimony between the two has long been

7. i.e., in Dicker's terms (Dicker, 1980)

acknowledged (e.g., Dicker, 1980, p.6; Utall, 1981). Crean (1984, p.188) notes that this proposition has frequently engaged philosophers debating the classical empiricist-associationist position.

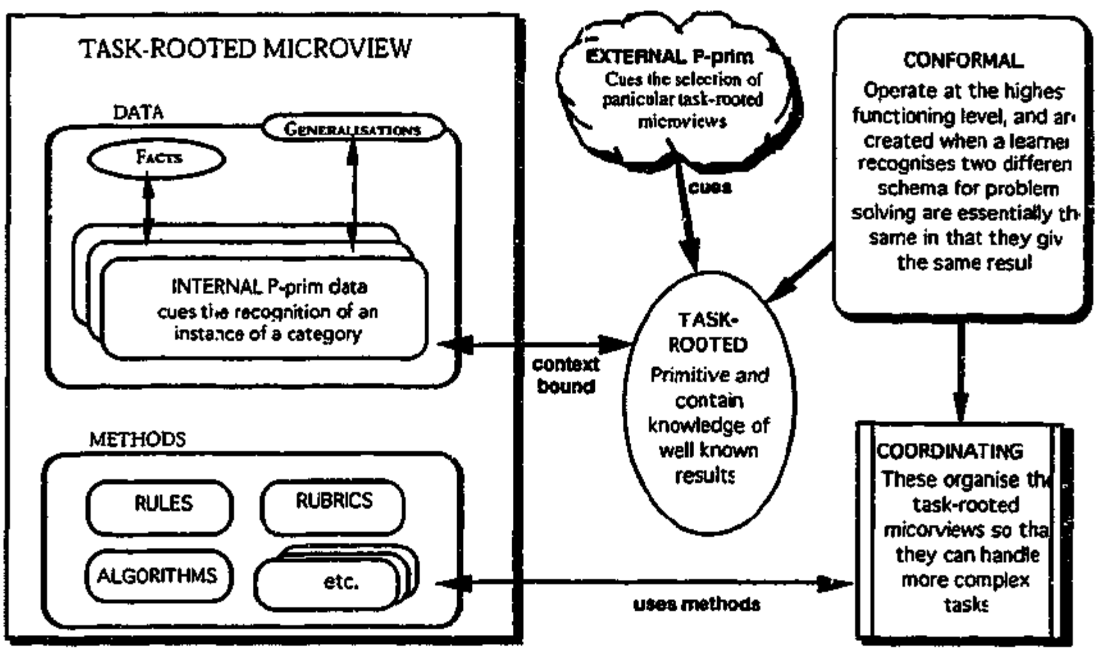
diSessa (1988; 1993b) explains the development of knowledge in terms of the incremental formation of cognitive structures based on increasingly sophisticated links and categorisations between essentially un-interpreted P-prims and more complex, learner-generated P-prims (such as 'springiness') that embrace a host of subordinate P-prims. In his model, increasing exposure to relevant physical events (such as observations and discussion of instances of falling, floating etc.) may lead to the development of a more sophisticated understanding of the nature of falling, but not necessarily to the Newtonian view, which requires active, directed intervention to develop in learners (e.g., Adams, 1988; Brna, 1991; Greeno, 1991; Niedderer & Schecker, 1992; Ploger, 1992; Roschelle, 1991b; Selman, 1994; Sherin, diSessa, & Hammer, 1992; Sherin, diSessa, & Hammer, 1993; White & Horwitz, 1987).

Lawler extends diSessa's P-prim model by reconceptualising them as 'microviews' which add methods[8] to P-prims — creating a 'task-rooted' microview, that includes both the P-prim data and the methods that act on that data (Figure 3-7 on page 59). These methods are dynamic, contextual, and temporal. 'Conformal' and 'coordinating' microviews act on and with task-rooted microviews to generate further knowledge structures by linking, relating, and queuing sets of task-rooted microviews into complex entities that encode more sophisticated knowledge than

8. in the cognitive science sense of an action associated with particular data.

do the individual microviews. This model explains the development of diSessa's complex P-prims. As well as developing increasingly sophisticated data structures, learners can also develop multiple contextual methods that operate on specific data (Lawler, 1979), explaining why students can hold multiple and conflicting views about particular events that are applied in different contexts. This also offers an explanation as to why intuitive understandings are so persistent over time (Fischbein, 1994, p.44), with new methods added, but not replacing existing ones; whichever method is used depends on the specific context at the time of use (cf. Keil, 1989, p.2).

Figure 3-7: Lawler's microview model (simplified) showing the roles of conformal and coordinating microviews in managing task-rooted microviews (after Lawler, 1979; Lawler, 1985)



In this study, I have used the model depicted in Figure 3-5 and Figure 3-6 as a general conceptual model for relating T-PCK and scientific content knowledge. It allowed framing the research in terms of whether the difficulties that the participants have in teaching physics lie in the data (their conceptual understandings), or the methods (their ways of interpreting and using the data for teaching, i.e., PCK). This is explored through a dialogue that relates content, context, and teaching issues in a semi-structured interview in which the subjects interact with a series of computer-based simulations of events drawn from the year twelve VCE physics curriculum.

Analysis of the resultant discourse provides a lens onto both their understandings of the underlying physics content knowledge as with traditional concept-oriented computer-based probes (e.g., diSessa, 1980; Hennessy et al., 1990; Lawler, 1985; Squires, 1987), and their ability to represent it and to communicate it. In this way it is hoped to develop a better understanding of specific aspects of the students' understandings of both physics, and the approaches they use to describe the relevant events to students. This knowledge will be used in developing more meaningful learning experiences and teaching strategies to use in their physics methods classes[9], particularly in the form of computer software that includes both cognitive and PCK aspects, in order to help them become more effective, and more competent, physics teachers. Lawler's model may well serve as the underpinning data model by providing a means of relating content knowledge to PCK. This thesis, with its attempt to use a computer-based approach to elucidating PCK (as well as conceptual understandings), is a step in this direction.

9. Classes concerned with developing pedagogical skills and knowledge for future physics teachers; not about developing physics content knowledge.

3.2 Topic-specific PCK

In this thesis I have adopted Magnusson, Krajcik and Borko's (1999) model of topic-specific PCK (T-PCK) in science education (Figure 3-3 on page 51) because it is both (arguably) the most clearly articulated structural model of PCK for science education, and also the model that is most closely aligned with the purposes of this thesis (Magnusson et al., 1999, p.110-5), providing both a structure to guide the research[10] (cf. Hirst, 1971), and a frame for viewing T-PCK. Their focus on representation — ways to represent specific concepts or principles is exactly the area of concern that led to this thesis.

This is an aspect of science education research that has long been recognised as being important (e.g., Pope & Gilbert, 1983, p.249), but which, while attracting significant research interest, (e.g., diSessa, Hammer, Sherin, & Kolpakowski, 1991; Driver, 1990; Flick, 1991; Greeno, 1974; Krupa, Selman, & Jaquette, 1985; Pallrand, 1988; Roschelle, 1991b; Wandersee, 1993; Wilson et al., 1987), has not generally been an integral part of science-education research programmes:

> Science education is concerned with making links: between explanation and understanding, between teachers and students. Yet the nature of these links has not been fully explored. (Pope & Gilbert, 1983, p.249)

Magnusson, Krajcik and Borko's model of PCK, however, provides both a structure and a rationale for the inclusion of 'representation' as an essential aspect of research in science education.

While it is not necessarily the purpose of this thesis to argue for the veracity and usefulness of the PCK model employed here, it is important to note that the creation

10. as discussed on page 47

of such nominal-kind categories (Keil, 1989, pp.25-58) as 'activity' and 'representation' is perhaps problematic in terms of their application to classroom observation, and related work (such as this thesis) as the former is directly observable and reportable, whereas the latter is both perceptual and interpretive (cf. Fodor, Garrett, Walker, & Parkes, 1980; Garner, 1974; Keil, 1989, p.10-14). In this thesis, this 'difference in kind' issue manifests itself as the difficulty of perceiving and interpreting elements of representation (i.e., as some element of PCK) amongst and within the participants' scientific content knowledge in their discussions of the various probes employed in this thesis.

3.2.1 Representation

Fischler (1987, p.67) identifies five cognitive roles for representation, noting that '...most people are unaware of their use of models[11] in problem solving and the way that they view the World':

1. Interpretation: sensory information that can be interpreted by using internal representations (models) of real-world objects.
2. Organizing function: may allow the organization of information so that similarities and differences between objects and events are more readily identified.
3. Questioning function: internal models lead us to ask questions about events.
4. Predictive function: internal models allow us to predict events that will result from actions.
5. Deductive function: certain representations can be used to make new knowledge explicit by allowing deductions to be performed on the original model.

Keil (1989, p.83) notes that the notion of representing nominal-kind constructs such as PCK is both complex and problematic, with inherent difficulties related to the nature of nominal kinds, and the domain-specificity of concepts. This, presumably,

11. i.e., mental models.

is the underpinning reason for the apparent lack of agreement about (the very few) examples of T-PCK in the science-education literature (e.g., Loughran et al., 2000, p.2). Keil (, p.83) further notes that, in regard to concepts, nominal kinds are used for several reasons:

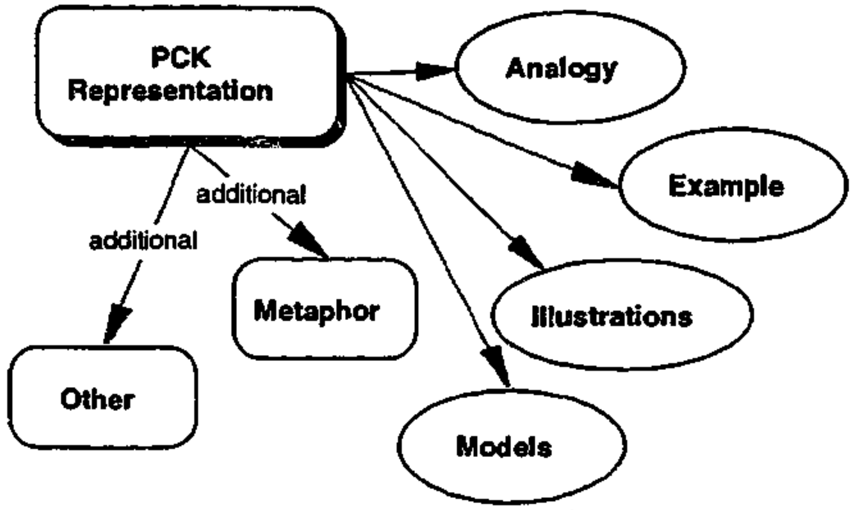
1. The domains are often easily demarcated by a few general principles.
2. The characteristic or defining paradigm is easy to use.
3. They can change over time (possibly due to the inclusion of other domains).

The items listed above apply to PCK, and have been beneficial to its uptake — given its 'general' nature, an apparently simple defining paradigm, and its ease of application to different domains. These same features however have also been harmful to its development — the lack of precise definitions or paradigms has made it difficult for researchers and practitioners to employ a common PCK framework in educational practice or research (e.g., Loughran et al., 2000; Niess & Scholz, 1999; Veal & MaKinster, 1999). This is particularly true of the area of representation in Magnusson, Krajcik, & Borkos' model (1999, p.99), where representation refers to:

> ...teachers' knowledge of ways to represent specific concepts or principles in order to facilitate student learning, as well as knowledge of the relative strengths and weaknesses of particular representations. We also include in this category a teacher's ability to invent representations to aid students in developing understanding of specific concepts or relationships. (Magnusson et al., 1999, p.111)

There are four categories of representation in this model — analogies, examples, illustrations, and models (cf. Vergnaud, 1998). The additional categories of 'metaphor' and 'other' were added for the purposes of this thesis to create a six-item structure for topic-specific representation as in Figure 3-8.

Figure 3-8: The PCK structure used for 'representation'. (after Magnusson et al., 1999, p.111)



The additional terms were included for two reasons. First, because this is a recent conceptual and structural model of PCK that does not appear to have been widely researched at the level of T-PCK (cf. Magnusson et al., 1999, p.127), it is likely that further elements of representation may develop over time (as discussed above), hence the inclusion of the category of 'other'. Second, the inclusion[12] of metaphor as a category was due to it's inclusion in Shulman's original description of PCK, a desire to have a category that could be used to capture the participants' use and development of metaphor, and because of the recognised importance of comprehending metaphors in developing an understanding of terms in conceptual development (cf. Duit, 1991; Keil, 1986; Pope & Gilbert, 1983). This seemed to be particularly important in the context of the participants of this thesis, who presumably have not developed a rich T-PCK, because such development would have to include an increasingly sophisticated understanding of the use of terms in context, appropriate analogies, examples, illustrations and models. Jonassen (1995,

12. Metaphor as an aspect of PCK is implicit in Shulman's early works.

p.183) notes that analogical or metaphorical reasoning is an important aspect of describing mental model development (cf. Staggers & Norcio, 1993). The use of metaphor therefore seems to be a potentially important aspect of T-PCK, and so was explicitly added to the model in an attempt to capture aspects of the development of richer PCK, i.e., the use of cross-domain metaphors which might be useful in relating items from different domains.

The difficulty that preservice teachers have in creating meaningful and effective representations is well known (e.g, Borko & Livingston, 1989; Borko & Putnam, 1996; Zembal-Saul et al., 1999, p.247), and indeed, is the origin of this thesis. The categories used here assist in articulating approaches to effective representation, and as such should be used more explicitly in preservice teacher education courses. In addition, they form the framework for the identification of elements of T-PCK in this thesis.

Magnusson et. al. (1999, p.112) note that methodologically '…teachers generally have not been asked directly about the representations they use in their science teaching; rather, information about teachers' knowledge has been inferred from their practice.' (e.g., Dagher & Cossman, 1992) In a seminal study of science teachers' use of representation, Sanders, Borko, and Lockard (1993) found that science teachers often had difficulty in creating appropriate and relevant representations 'on the fly' in response to sustained student questioning. Because the teachers had the most difficulty with areas they were least familiar with, Sanders et. al. conclude that the ability to create effective representations is strongly related to teachers' understandings of the content knowledge that they are teaching. Magnusson et. al. (1999, p.112-3) however, argue that this finding should not be taken as implying that an increased understanding of scientific content knowledge necessarily leads to the use of better representations in science teaching.

3.2.1.1 Analogy

The use of an analogy is, in logic terms, the process of reasoning from parallel cases (Fowler & Fowler, 1975, p.41). Clement (1981, p.1) regards this as occurring '...when a subject first spontaneously shifts his attention to a situation (B) which differs in some significant way from an original problem situation (A), and then tries to apply findings from B to A.'[13] Clement (1981, p.17) also argues that for this to be successful, three conditions must be met:

1. Given the initial conception A, the analogous conception B must 'come to mind'.
2. The analogy relation must be 'confirmed'.
3. Conception B must be 'confirmed'.

Wittrock and Alesandrini (1990, p.501) found that 'Teaching procedures, such as instructions to generate analogies and summaries can facilitate comprehension and knowledge acquisition by stimulating learners to use their analytic and holistic abilities ...', suggesting that student-created analogies might be equally as important as those used by the teacher in developing conceptual understandings. When they intersect with opposing epistemological, pseudo-scientific, or religious beliefs (e.g., Venville & Treagust, 1997), some analogies may be contentious and disputed, potentially leading to learner confusion. Thagard (1992) notes that the effectiveness of an analogy can be related to pragmatic, semantic, and structural

13. cf. Clement, 1978, Nagel, 1961.

factors. For example, Jim[14], a participant in this study, attempts the following analogy to explain the rotation of a falling body[15]:

> ...there was a sort of 'cat-like' force that turned him onto his feet...

While this clearly relates the twisting motion of falling cats to the falling body (a parallel case), it does not provide any sensible mapping onto concepts of Newtonian physics; according to Clement's three criteria for a successful analogy (page 66), there is no obvious relation to understand, nor obvious *second* conception to be confirmed. Rather, the attempted analogy fails in its intended purpose because it merely presents a second *example* (a cat) of the original context. This is an example of a 'structural' problem in the analogy.

Gilbert (1989) determined that the use of analogy, metaphor, and simile in biology textbooks had little effect on student achievement, and that they impacted negatively on student attitudes towards Biology. In examining authors' use of analogy in Chemistry textbooks, Thiele (1991; 1992) identified three significant aspects:

1. Authors assumed classroom teachers would effectively use the analogies, despite no evidence that teachers have pedagogical content knowledge in this area.
2. The frequency of analogy inclusion implies an unwillingness by authors to use analogies in textbook situations.
3. The authors are unfamiliar with research guides regarding analogy presentation results.

This suggests that textbook authors are employing analogies in their texts without a real understanding of the difficulties that teachers may have in presenting them (cf. Carlton, 1999), and the ways in which they might be interpreted or misunderstood.

14. see Section 7.2.5 on page 281.
15. see Section 6.4.3.3 on page 213.

Commonly used analogies in science education include the flow of electric current being related to water in pipes, batteries to pumps, and resistance compared to water flowing uphill or to mechanical friction[16] (e.g., do Couto Tavares, Boa, & de Olivera, 1991; Rodriguez, 1979; Shipstone, 1989, p.46; Stocklmayer & Treagust, 1994; von Rhoneck, 1985). A more subtle analogy is the use of the sublimation of Iodine (i.e., solid to vapour), which produces a visible purple vapour, to explain the evaporation of liquids (Stavy, 1991).

The use of an analogy implies that the learner can understand the parallel case being presented, and can then transfer, or relate, the relevant ideas to the particular case being examined. The challenge in using an analogy is to ensure that students move on from the analogy to develop the desired understandings. This can be problematic because there is no guarantee that this will happen. For example, the quantum wave-particle duality of matter is usually related to both waves and particles separately, without necessarily addressing such questions as 'What are electrons really like?' (Mashhadi, 1995, p.314), so leaving the student at step one or two of Clement's three conditions for a 'successful' analogy (above). When asked '...when diagrams of atoms or molecules are drawn, they do not show individual electrons in orbit but refer to electron orbitals or electron clouds. Why is this?' (Mashhadi, 1995, p.328), 25% of students asked held mechanistic views such as:

> Because nobody actually knows the position of an electron because they move around so fast, and they are very small. (Mashhadi, 1995, p.321)

16. see also (Wandersee, Mintzes, & Novak, 1994), p.182.

This shows that the students have presumably understood the orbital analogy, but have failed to develop the desired quantum-mechanical (i.e., wave function) model that the use of the analogy was attempting to develop.

An important aspect of the use of analogy is that teachers should be able to identify the *best* analogy for a particular teaching situation, and to understand why it is the best. For example, Brown and Steinberg (1993, p.16-17) argue that air is a better analogy than water for explaining the flow of electric charge, because students know, or can easily be shown, that air is compressible and that water is not. The air analogy '...makes it vastly easier for students to visualize compression of charge and the resulting effort-to-expand called "electric pressure." ' (p.16) Further, while water flow requires gravity, compressed air will expand spontaneously, providing a better analogy for understanding why 'electric pressure' results in a flow of charge (p.16). Such an appreciation requires teachers to have a strong content knowledge base in order to understand the subtle differences between analogies. (This issue is also raised in the following discussion on the use of metaphor.) As well as knowing the best analogy to use in a particular context, it is equally important for science teachers to represent the scientific knowledge it relates to correctly — after allowing for the contextual aspects of T-PCK raised previously. For example, Dagher & Cossman (1992) found that about 25% of the teachers in their study (n=20) used scientifically inaccurate explanations in teaching science. The use of erroneous statements is likely to confound students and hinder them in relating analogies to the actual case under consideration (cf. Clement, 1978).

3.2.1.2 Examples

This category refers to the use of different instances of the attributes of a concept to help students to understand it, in a process similar to older approaches to learning concepts by learning lists of the characteristic and defining features (cf. Keil, 1989, p.47). Examples may be presented in many formats other than physical. These can be, for example, textual, verbal, graphical, mathematical (as in examples of how to solve particular types of problems or to apply mathematical formulae and processes), visual (as in the performance of an experiment or process), or computational — in which case there may be a combination of graphic (including multimedia media types such as video, audio, animation etc.), algorithmic, mathematical, or textual forms (e.g., Carpenter & Just, 1992; Chien, 1997, 1999; Clayson, 1988; Cockburn & Greenberg, 1995; Dede et al., 1996; diSessa, 1975; diSessa & White, 1982; Feicht, 1999; Feurzeig & Lukas, 1972; Gillies et al., 1996; Hennessy et al., 1990; Morse, 1995; Murray, 1990 1134; Ploger, 1991; Roschelle, 1991b).

3.2.1.3 Models

Models, both physical and abstract, give shape to a form, document, or argument (Fowler & Fowler, 1975, p.778). Models may be presented in many formats other than as physical models (such as a plastic-ball and wire model of a molecule), including those discussed as types of example formats in the previous section. A model, however, differs from an example because it contains adequate information to provide the learner with a causal explanation[17] of the phenomenon under

17. as represented in the model, and dependent, therefore, on the accuracy and detail of the model.

consideration. While lists of properties might be used to define a concept, such as gravity, such properties alone do not result in a causal model. For example, Newton's second law, whether presented as a textual or mathematical model (Section 4.3.1.2), contains the information needed to understand the relationship between nett-force and acceleration. However, simply stating that a nett force of 1N acting on a mass of 1kg produces an acceleration of $1 m.s^{-2}$ is an example and not a model, because it does not contain generalisable, causal information. A student might, however, guess that there is a linear relationship, but there is no explicit information about that in the example. It is the inclusion of causality that fundamentally defines models and distinguishes them from examples.

The simplification of models for particular learners can generate unanticipated problems if the limitations of the model are not made clear. Belloli (1983), for example, found that students were confused and led to erroneous conclusions from the overuse and misuse of the circle notation to represent aromaticity in polycylic aromatic hydrocarbons (PAH). Use of the circle model implies a uniform distribution of electrons around carbon rings in the PAH molecules (this is the causality that underpins its use as a model). However, except for symmetrical PAH molecules[18], this is not generally the case, with significant charge polarity facilitating many chemical reactions that could not easily be predicted on the basis of a uniform distribution of charge around the PAH rings. This is a similar type of issue to that raised previously (Figure 3-6) in the use of speed rather than acceleration with junior science classes — it is adequate for some simple examples,

18. e.g, Benzene, in which each carbon atom has an identical molecular structure by virtue of the single attached hydrogen atom, and an equivalent symmetry in the molecule to every other carbon atom.

but fails in more complex cases. Metallic bonding also presents similar opportunities for confusion, particularly when represented in different ways over time in accordance with particular curriculum paradigms (Maria de Posada, 1999). Such confusion about molecular models, and what they represent, is common (Wu, Krajcik, & Soloway, 2000, p.121). With the use of computer software that allowed students to develop molecular models, and to view multiple representations of them simultaneously, Wu, Krajcik, and Soloway found that student use of models can facilitate the development of their mental models and images (Wu et al., 2000, p.121). This suggests that teachers should, perhaps, be constantly challenging their students understandings of particular models, and challenging them to come up with better models of their own.

3.2.1.4 Metaphor

A metaphor applies a name or descriptive term to an object to which is does not normally apply (Fowler & Fowler, 1975, p.763). Black (1979, p.17) identifies three classes of metaphors:

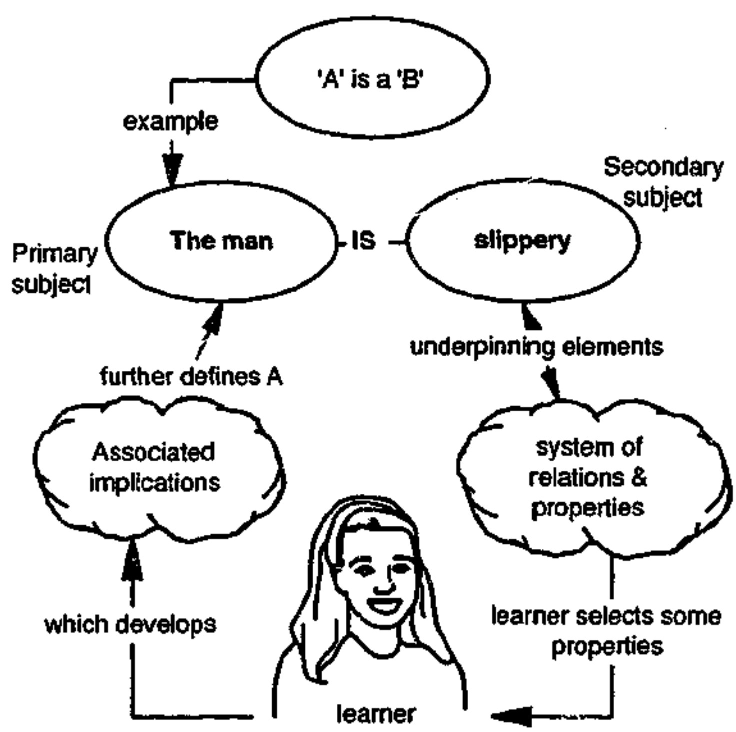
1. Substitution: the sentence can be replaced with a set of literal sentences.
2. Comparison: the sentence can be reduced to a paraphrase.
3. Interactive: complex interaction between the elements of the metaphor (as in Figure 3-9)

In Black's view, understanding metaphors that use substitution or comparison is a relatively simple cognitive processes[19]. Interactive metaphors, however, present greater cognitive challenges. For example, an interactive metaphor such as 'The man is slippery'[20]; relates properties from two domains — texture types and

19. for the recipient of the metaphor
20. cf. 'The man is honest.'

personality traits (Keil, 1989, p.83), both of which need to be understood on their own, and then interpreted in the light of the other. Figure 3-9 depicts Black's model of interactive metaphors (Black, 1979, p.28-9), in which the learner selects some properties of the secondary subject and develops a set of 'associated implications' that help to redefine the primary subject in the light of the properties drawn from the secondary subject. Black argues that this is a mutually reciprocal process, with the understanding of the secondary subject being modified in response to applying some of its properties to the primary subject.

Figure 3-9: Black's model of an interactive metaphor (after Black, 1979, p.28-9).



The purpose of a metaphor is to provide a rational bridge, acting as '...an epistemological chasm between old knowledge and radically new knowledge' (Petrie, 1979, p.440). Black (1979, p.31), however, cautions that '... every metaphor is the tip of a submerged model' because understanding the related terms in a metaphor requires a good understanding of the properties that define them, especially in the case of an interactive metaphor as above. This can be difficult if the terms originate in different domains, (as above). Understanding cross-domain metaphors requires '...a knowledge of the structural relationships between many of the concepts in each domain' (Keil, 1989, p.84), implying that a lack of such knowledge in either or both domains would make it difficult, if not impossible, for the metaphor to be understood (cf. Keil, 1989, p.84; Lehrer, 1978; Tourangeau & Sternberg, 1982). This presents a challenge to science teachers because, on this basis, the widely held scientific misconceptions of school children across most science content areas (e.g., Duit & Pfundt, 2000) could make it very difficult for children to relate specific terms drawn from different content domains. The use of metaphors in learning (i.e., by learners) can also affect the ways in which those learners create and represent models of the phenomenon under consideration (e.g., Christidou, Koulaidis, & Christidis, 1997), suggesting that the categories of metaphor and model as used by Magnusson et. al. should be seen as strongly interrelated and dynamic, rather than as separate and static entities. However, examining students' understandings of teachers' use of metaphor may provide valuable insights into student learning (e.g., Thomas & McRobbie, 1999).

3.2.1.5 Illustrations

While included, but not explicitly *defined* in the model, for the purpose of this thesis, it is taken in its literal sense; 'to make clear, to explain, ... to elucidate, ...' (Fowler & Fowler, 1975, p.604). An 'illustration', therefore, for the purposes of this thesis, is regarded as having a more complex structure than the entities above, and which may make use of analogies, examples, metaphor, and models. The use of such multiple forms of representation within a *single* explanation[21], has been taken as the working definition of an 'illustration' in this thesis. For example, returning to the electric circuit context, in trying to explain Ohm's law, a teacher may well discuss the water flow analogy (as above) and also, in the same explanation, relate water pressure to voltage, and water flow to electric current. Because these two representational forms are logically bound together in a single explanation, this constitutes, in terms of the definition adopted here, an illustration rather than the separate use of an analogy and a model. Methodologically, such cases in the data can be multiply coded, so that the use of model, metaphor *and* illustration can be identified in the data.

3.2.2 Speculations on the development of T-PCK

Given the essential relationship between T-PCK and the effective use of analogy and metaphor discussed above, it is tempting to speculate that the development of T-PCK might parallel the development of content knowledge in a framework perhaps similar to, for example, Forbus and Gentners' (1986) Qualitative Process theory; a sequential cognitive developmental model. In a similar way to that in which Forbus and Gentner argue that content knowledge development consists of four stages from proto-histories to causal corpus to qualitative and then quantitative models, it is not difficult to imagine that the development of teachers' understandings of the appropriateness and accuracy of analogies and metaphors

21. as opposed to their use in several discrete acts of explanation.

might occur in some similar sort of sequence in parallel with content knowledge growth, or perhaps more feasibly, with their experience in teaching. Following this line of argument, it would be expected to see, in Forbus and Gentners' terms, 'richer and more articulate' analogies and metaphors being developed and used over time, along with an increasingly sophisticated understanding of their nature and limits (cf. Clermont, Borko, & Krajcik, 1994). While this is speculation, the issue that is addressed — the relationship between content knowledge development and T-PCK certainly needs further research, as the current literature has little to say on this. However the proposition that the development of more general aspects of PCK should proceed in parallel has begun to be adopted (e.g., Niess & Scholz, 1999; NSTA, 1999).

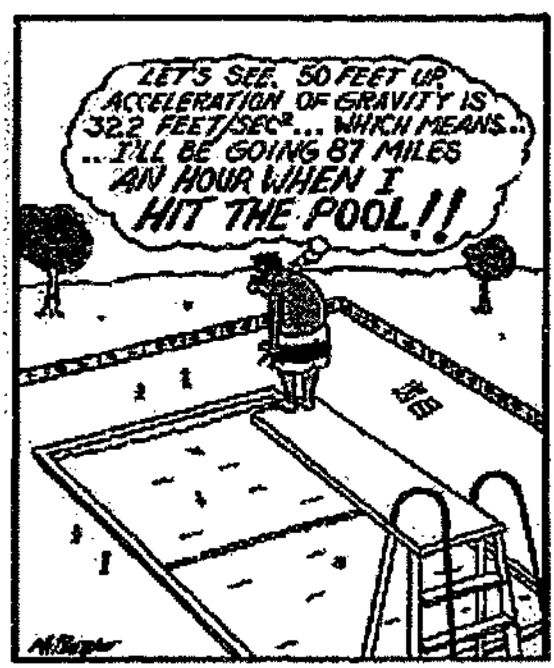
3.3 Chapter Review

In this chapter, the notion of knowledge bases for teaching were examined in the context of Shulman's notions of Pedagogical Content Knowledge, and the particular aspect of PCK of relevance to this thesis, T-PCK[22], was elaborated. The attributes of the specific representational aspect of T-PCK that are examined as part of the research for this thesis were reviewed in order to provide insight into the nature of the data that might be collected from the participants during the interview phase of this research.

22. See "Topic-specific PCK" on page 61.

Chapter 4

On knowing mechanics



There are times when being a whiz at physics
can be a definite drawback.

4

On knowing Mechanics

> One afternoon several years ago the writer was asked to proctor an examination in elementary physics to be administered to a large room full of army trainees. As he strolled the room waiting for the examination to begin he overheard many snatches of excited, apprehensive conversation — of which one significant piece has haunted him ever since: "Sure, I know F = ma, but what's F? what's m? what's a?"
>
> (Weinstock, 1961)

4.1 Introduction

In this chapter I review a selection of research about learners' understandings of Newtonian mechanics (particularly where gravity is a factor) that is relevant to the VCE area of study that forms the context of this thesis.

The purpose of this review is to identify research findings about learners' understandings of gravity in order to assist in the subsequent interpretation and analysis of participant data, particularly in the categorisation of responses as arising from either the content-knowledge or T-PCK[1] domains of Shulman's model. In this section, the findings of the selection of relevant studies that are reviewed below provide indicative outcomes in the form of student understandings about the area that might be expected from the participants of this study. Because the studies reviewed here have almost exclusively adopted a science-content-knowledge approach to student misconceptions, it is assumed that the findings of such research

1. i.e., topic-specific PCK

will be indicative of participant responses that can be categorised as belonging to the science content knowledge domain, unless there is evidence to the contrary.

While the majority of studies reviewed here were conducted before 1995, when the notion of exploring explicit misconceptions in depth in order to develop explicit remediation began to give way to the more holistic approach of documenting and exploring learners' 'stories' (A. A. DiSessa, personal communication, 11/08/94), they are still timely as recent research shows that many of the issues raised in those earlier studies are still explored in the research literature (e.g., Bar, Sneider, & Martimbeau, 1997; Galili, 1996), and are extant in the public consciousness (e.g., Channel Seven, 2000; FOX Television, 1995). This raises the issue that perhaps an opportunity to more closely align misconceptions research with pedagogical aspects of science teaching such as Shulman's model (as in thesis), and a concomitant focus on teaching, has been lost because of the impact of post-structuralist and post-positivistic paradigms on science education research in the 1990's, especially as similar approaches to employing Shulman's model in technology-based teacher–development programs have shown considerable potential in this regard (e.g., Tsui, Coniam, Sengupta, & Wu, 1994).

The review starts by considering 'historical' models of mechanics for two reasons; first, because the literature suggests that aspects of such models are likely to be found in many of the participants of this study (e.g., Eckstein & Kozhevnikov, 1997; Nersessian, 1989), and second, because they provide a convenient framework for categorising a disparate range of research findings. Perspectives arising in non-western cultures (e.g., Peat, 1997; Saddar, 1988; Saddar, 1989) are not addressed here because they fall outside of the focus on the Eurocentric development of

Newtonian theory. Newton's theory is then briefly discussed and the chapter concludes with a review of research on learners' conceptual understandings of gravity, planetary systems, and orbital motion — areas that form the focus of the VCE physics content at the heart of this thesis. The order in which the models are reviewed (Aristotelian, Galilean, Newtonian) should not be taken as implying a sequential development of knowledge by learners moving through these models — Schecker (1992, p.71) for example notes that '...there is no linear shift from peripatetic notions to Galilean or Newtonian concepts' (cf. Carey, 1988).

4.2 Historical models of mechanics

> Philosophers and historians have emphasised that the construction of the principle of inertia constituted the essence of the transition from Greek and medieval thought to the incontestably modern science of Newton's *Principia*.
>
> (Nersessian, 1989, p.166)

An understanding of the development and ontology of the field is arguably an important part of developing an understanding of mechanics, and for understanding learners' mental models of mechanics (Giannetto et al., 1992, p.361), and also because of the recognition of the relevance of historical considerations in science education research (e.g., Giannetto et al., 1992, p.359; McCloskey & Kargon, 1988; Nersessian, 1989, p.163-5; Shanon, 1976) and teaching (e.g., Bush, 1989; Bush & King, 1972; Galili, 1996, p.233; Gill, 1977).

Conceptual change studies have provided significant insights into learners' mental models of mechanics, either as snapshots of understanding (as in this study), or as longitudinal studies (e.g., Andaloro & Bellomonte, 1998; Bar, Zinn, Goldmuntz, & Sneider, 1994; Bliss, 1989; Bliss, Morrison, & Ogborn, 1988; Brown, 1989;

Clement, 1983; Eckstein & Shemesh, 1993; Graham & Berry, 1993; Guidoni, Porro, & Sassi, 1995; McCloskey, 1982, 1983a; McCloskey, Caramazza, & Green, 1980; Minstrell & diSessa, 1994; Piburn, 1988). Many of these show that in developing an understanding of Newtonian mechanics, students may hold, or pass through, a series of mental models that have *components*[2] with *strong similarities*[3] to those underpinning 'historical' models of mechanics (e.g. Clement, 1983; diSessa, 1982; Eckstein & Shemesh, 1993; McCloskey, 1983b; McCloskey et al., 1980; McCloskey & Kohl, 1982; Nersessian, 1989; Pfundt & Duit, 1991; Sequeira & Leite, 1991; Watts, 1982). Lochhead (1985, p.5-6) notes that such classifications are useful ways of describing novice understandings. These historical components can be considered to be 'zero order models' (Clement, 1982). Because of the frequency with which they are reported in the literature, they are likely to be held, to varying degrees, by the subjects of this study (cf. Ebison, 1993; Sequeira & Leite, 1991).

There is no compelling evidence, however, to suggest that students classified as holding an Aristotelian view acquire a Newtonian view by passing through a Galilean state (e.g., Schecker, 1992, p.71). Indeed, given that the historical models represent, at best, loose metaphors for learners' *actual* mental models, this would be surprising. Indeed, Lythcott (1985) dismisses the notion of the parallel development of historical models and individuals as a flawed recapitulation theory that serves principally as a convenient mechanism for simplifying descriptions of students' understandings — one that detracts from a more realistic appraisal of their

2. c/f fully developed, coherent, models.

3. not always faithful to the model i.e., few students are truly Aristotelian *across* concepts

actual mental models. In this study, the use of historical models is limited to the role of a convenience in classifying a disparate range of non-Newtonian models as an aid to analysis.

It should also be noted that changes between the following models represented in the figures below, while *only* appearing as changes in relations, entities, and kinds[4] may involve enormous cognitive challenges for learners as concrete entities (properties) become abstract relations, and syntactic similarities effectively disguise significant changes in meaning (cf. Keil, 1989, p.83). Additionally, in the case of the Newtonian model, its fully abstracted entities have no physical manifestation, existing only as mental models (Nersessian, 1989, p.178).

4.2.1 Models and deviation

Driver and Easley (1978) identify '*nomoethic*' studies as those in which knowledge '...is measured by its conformity to, (or deviation from), a standard knowledge base.' (Wandersee et al., 1994, p.179) Such studies consider the mismatch between the learner and a 'correct' model, such as the Newtonian model of mechanics. Clearly much of the research mentioned above falls into this category because the historical models that they refer to are axiomatically 'standard knowledge states' to which learners' mental models are compared. Wandersee (1994, p.179) identifies a large number of terms that attempt to describe the observed deviation from such standard models. Many of the terms are closely related, e.g., 'errors, naive conceptions, erroneous ideas, misunderstandings...', are often not precisely

4. i.e., between entities of similar kind, as in gravity is a *kind* of 'active' force in the Newtonian model (see Figure 4-8 on page 105).

defined, and are located temporally in the literature, being supplanted as subsequent research generates new perspectives and epistemological stances. Their persistence, however, contributes to a confusing literature base that has not only accommodated major paradigm shifts in the nature of educational research, but which also has accommodated similar shifts in paradigms of cognition and learning. For example, behaviourist, information-processing, constructivist, and connectionist theories have all been applied to the study of 'misconceptions', and each makes particular claims about the field. Driver and Lythcott also define *idiographic* studies as those in which the student's understandings of particular contexts, concepts, and objects are '...probed, studied, and analysed on their own terms.' (Driver & Easley, 1978, p.79; Wandersee et al., 1994, p.179)

Gunstone (1989, p.643) notes that attempts to categorise *researchers* into either category are problematic for two reasons. First, because although a particular methodology may be employed for a specific research question, quite different ones may be applied to other questions. Second, '...researchers' viewpoints may evolve with the field.' (Wandersee et al., 1994, p.180) This study, with its focus on the subjects' difficulties in teaching with the Newtonian model, has the characteristics of a nomoethic study, in that the conceptual difficulties that are of interest are deviations from the Newtonian model. At the same time, there is a strong idiographic flavour to the focus on the importance of pedagogical issues: an example of Gunstone's point about the use of specific methods for specific questions.

4.2.2 Aristotelian-based medieval models

Medieval theories of motion evolved from Aristotle's theory of motion: one concerned principally with describing an object's change of position, in which motion is regarded as a process rather than a state — a major difference from subsequent models. This coarse-grained, commonsense model provided functional solutions to everyday problems (Ebison, 1993). It was modified over time until replaced by the Newtonian model, and a solution to the problem of the structure of the heavens was developed through the work of Brahe, Copernicus, Galileo, Kepler, and Newton many centuries later (Hurd & Kipling, 1964, p.121).

4.2.2.1 FEATURES

Aristotle's theory was not only concerned with 'mechanics' — it was a universal theory of change that applied to all objects, both living and inanimate; a general process that affected all *local* entities including biological and geological changes. Different laws applied to Heavenly and terrestrial objects (Hurd & Kipling, 1964; Nersessian, 1989, p.167). This generality and the lack of common understandings, scope, or terminology makes it difficult to relate Aristotle's writings to those of Newton, Kepler or Galileo, as does the lack of an Aristotelian mathematical treatment of instantaneous motion. In Figure 4-2 the key features of the 'medieval' model of motion are shown by means of an entity-relationship map in which entities are linked by lines that represent one of three different types of links.

The types of links in this diagram, and in subsequent similar figures, are:

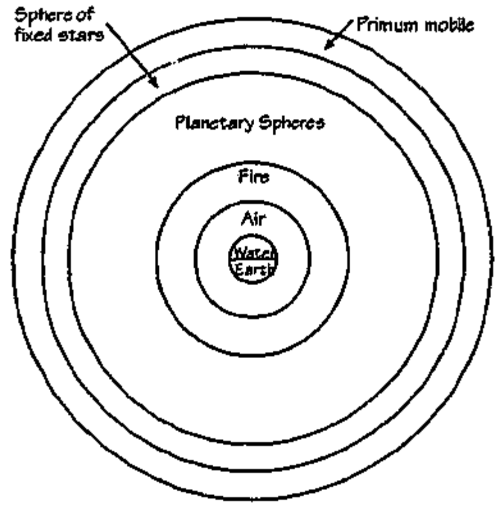
- *Kind* links (K) - these identify entities of similar nature: e.g., Natural and Local motion are both *kinds* of Motion.
- *Property* links (Pr) - these show the properties of an entity: e.g., occupied *Space* is both *finite* and *closed*.
- *Relation* links (R) - these identify causal relationships: e.g., a *projector* imparts impetus to a body.

This diagram is presented here to provide the reader with a visual map of the content of the review, as well as a visual representation that allows the structural relationships within the model to be examined prior to the following review that discusses the model. The review frequently refers to aspects of Figure 4-2 by the annotations on the links, e.g., K_3.

4.2.2.1 (a) Features of the Aristotelian model of motion

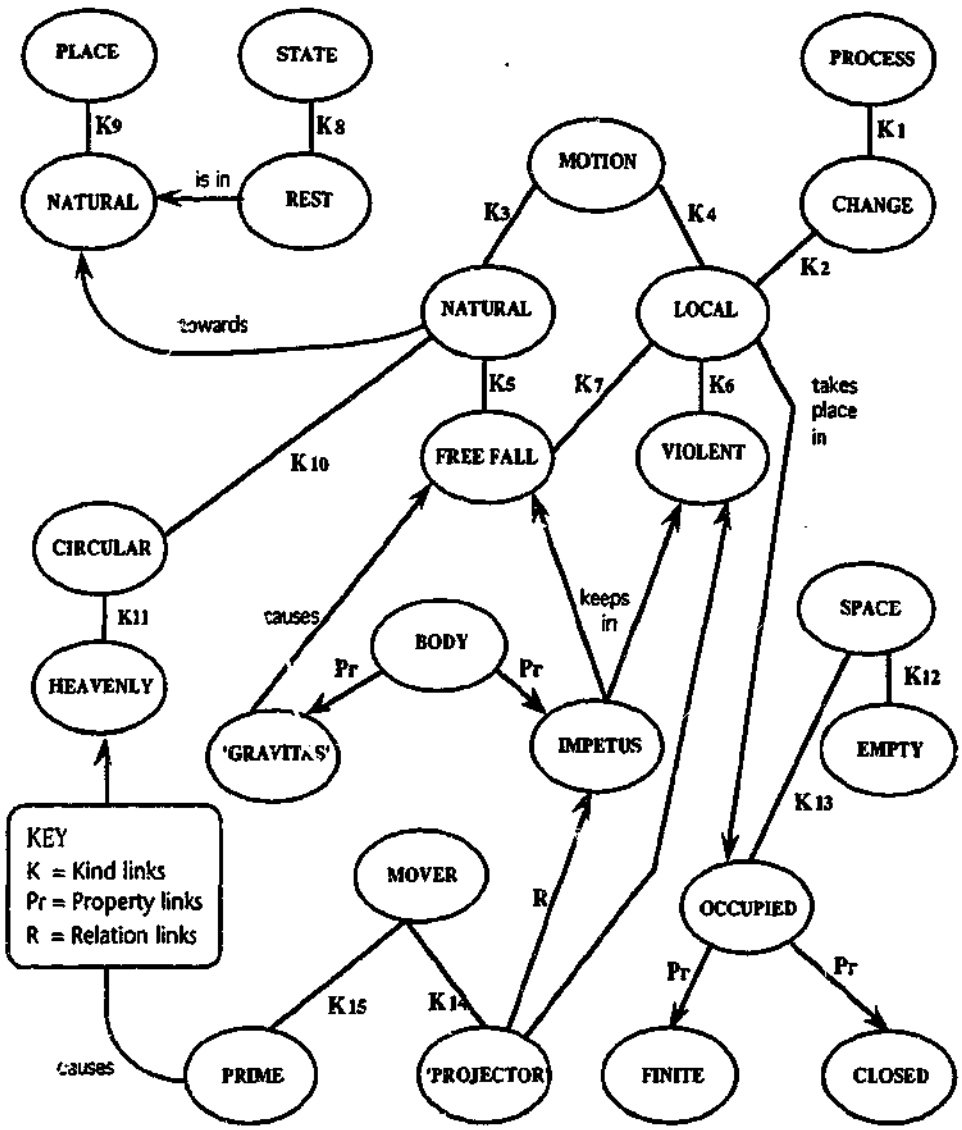
In accord with Platonic theory, the four basic elements — earth, air, fire, and water, each had a 'proper place' and a 'natural' motion according to what they were observed to do in nature (cf. Figure 4-1).

Figure 4-1: Diagram of the medieval concept of the World structure. (after Holton, Rutherford, & Watson, 1968, p.37)



Water and earth were 'heavy', and their natural motion was to move downwards towards the Earth. Fire and air were light, and their natural motion was to move upwards (Lythcott, 1985, p.430; Toulmin & Goodfield, 1963, p.104).

Figure 4-2: Key features of the medieval model of motion. (after Nersessian, 1989)



These motions were in competition with one another, and so the direction of an object's natural movement was determined by the most abundant element within it. Both 'heaviness' and 'lightness' were sensory properties that had no connotations of any numerical value or attributes. The concept of *Gravitas* (heaviness) was introduced in the early medieval period in an effort to have a quantifiable concept of heaviness. There was no notion of gravity (in the Newtonian sense), nor any explicit notion of 'attraction' between bodies, other than being expressed as motion towards an object's natural place.

'Natural' motion was axiomatically natural, occurring without assistance (K_3) only in 'occupied space' (K_{15}). In the heavens, motion was circular and *perfect*, and on the Earth, it was linear (Galileo, 1934, Ch.1-4; Hurd & Kipling, 1964, p.29). In the heavens, the planets exhibited natural motion as they moved in 'endless and perfect' circular paths (K_{10}, K_{11}) without an external agent because this was their natural motion and tendency. A 'prime mover' (K_{15}) was responsible for such heavenly motion, but it did not act on earthly bodies. Violent motion (K_4) was any motion that opposed the nature of a body to move, and required an outside agent to act (K_6,K_7).

Motion and rest are opposite and opposing categories. Rest is the natural state of earthly bodies (K_8) when they reach their natural place (K_9) which is as close to the Earth as possible. A state of rest therefore needs no explanation, but motion does, whereas in the Newtonian model they have equal ontological status, representing two different instances of velocity. They form parts of a continuum, rather than being different entities (Nersessian, 1989, p.167). Free fall could be both natural (K_5) — caused by a body moving to its natural place, or violent (K_7) — by being thrown downwards, or as part of projectile motion.

Motion such as a cart being dragged over stones, was described as motion *against a constant resistance*, which is different from Newton's model of motion in the *absence of resistance*. Aristotle's 'rules of motion' were rules of proportion that described motion within a carefully defined scope (Toulmin & Goodfield, 1963, p.106). His two general principles of motion were concerned with the relationships between speed and effort and between speed and resistance.

4.2.2.1 a.(1) Principle 1: Speed and effort

Aristotle's first principle was based on a belief that all motion was a balance between effort and resistance — bodies moving *against a constant resistance*, in which greater effort produces greater *speed*[5]:

Equation 4-1 Aristotle's relationship between speed and "effort"

$$\text{Effort} \propto \text{Speed}$$

Experimental deficiencies are believed to have led to this model, due to a failure to recognize a brief period of initial acceleration, a problem also later faced by Galileo (Sherman, 1974). Observations of real world events would therefore have suggested a model that was consistent with Stoke's law[6] — constant velocity after a short initial acceleration (Weast & Selby, 1967, F86):

> The rate at which a body moves is in proportion to the effort exerted on it, and inversely proportional to both its bulk and the resistance opposing its motion. (Toulmin & Goodfield, 1963, p.208)

An example of this model would be a ball bearing quickly reaching terminal velocity while falling through a viscous liquid such as oil. This also led to the incorrect belief that a heavier body fell faster than a light body: a belief that persisted until disproved by Galileo's systematic experimental observations of falling bodies. Similar beliefs are commonly held by school children and college students (e.g., Kass & Lambert, 1983, p.384).

5. cf. a constant *acceleration* in the Newtonian model.
6. as related to motion in viscous fluids, not the mathematical theorem of surface integration.

These terms 'effort' and 'bulk' (above) should not be read as directly corresponding to 'force' and 'velocity' respectively, as (a) those terms are contextualised within the Newtonian model, and (b) they relate to motion viewed through a different paradigm. While they are commonly understood today, they have *no direct meaning* in the context of Aristotle's writings. In regard to other Newtonian concepts, Aristotle only mentions acceleration in general terms in his *Physics*, and fails to differentiate it from speed (Toulmin & Goodfield, 1963, p.234). He did not formulate a concept similar to momentum, which would have helped to explain projectile motion.

The concept of instantaneous velocity[7] was problematic for Aristotle because the division of a 'length' by a 'time' would not produce a 'pure' ratio, and this would break the then extant Platonic rules of proportion (Toulmin & Goodfield, 1963, p.103).

4.2.2.1 a.(2) Principle 2: Speed and resistance

The relationship between speed and resistance to motion was examined through the question *for a given effort, how much time does it take to move a body through a given distance?* Arguing that the answer depended on the resistance that the object experienced, he concluded that...

> The less resistant and more incorporeal and easily divided the medium, the faster in proportion will be the movement. (Toulmin & Goodfield, 1963, p.107)

He assumed that this rule of proportion applied in air, and that the short time of fall in air (as compared to water) was therefore due to the 'thinness' of air. This

7. cf. Zeno's paradox of instantaneous velocity (Toulmin & Goodfield, 1963, p.113)

conclusion was accepted because it adequately represented many commonly observed motions. This reliance on ratios also led to the rejection of the possibility of a vacuum (void - K_{12}) because of the illogical results obtained as he approached the boundary condition of having no medium to offer resistance — in which case the object, having no resistance, would take zero time to fall. He therefore concluded that a vacuum could not possibly exist.

4.2.2.2 PROBLEMS WITH THE MODEL

Aristotle's model provided reasonable kinematic explanations of everyday motion, but was unable to give satisfactory explanations about the dynamics of motion, failing to explain two key local phenomena — projectile motion and free fall. First, freely falling objects had eventually been shown to accelerate, and this contravened the theory — there was no explanation for such an event. Second, projectiles, instead of immediately falling downwards when no longer being pushed, or constrained by any mechanical device, continued to move in the same initial direction of motion for a period before eventually falling, which they should have done instantly according to Aristotle's theory. While Aristotle was aware of aspects of these conflicting observations, they remained curiously un-addressed.

4.2.2.2 (a) Moving 'down', and gravity

Motion downwards (falling, sliding, or moving by virtue of being dragged by an object falling downwards) held a special place (Lythcott, 1985, p.430): his arguments on falling objects were about objects moving to their 'proper place' rather than for a mechanism of motion (cf. Galileo, 1934, Ch.VII). He was adamant that *no force acted on falling bodies* — especially not an attractive force from the

Earth. He also argued strongly against the notion of a medium affecting the motion of a falling body in any terms *other than* as an excess of heaviness or lightness, thus avoiding the notion of a gravitational force. 'Gravitas' was an intrinsic component of a body, and was not caused by any external influence, as opposed to the Newtonian formulation of weight which requires an interaction of a mass with a gravitational field. A body could, however, be interrupted from falling by some obstruction, such as a column supporting stones in an arch, but when the obstruction was removed, the body would resume falling to its natural place.

4.2.2.2 (b) Impetus

The concept of *impetus* arose from the need to explain violent projectile motion. Aristotle originally explained projectile motion by adopting Philoponos's idea of 'incorporeal moving powers' that postulated that a 'mover' (K_{14},K_{15}) such as a bat or a hand imparted a 'moving power' to the air in its immediate surroundings (Toulmin & Goodfield, 1963, p.242). This moving power was then transmitted through the air as the object moves through it, so pushing the object along its path until it runs out. This is exemplified by the case of air rushing in behind a moving arrow or spear in order to keep it moving. Kass and Lambert identified similar beliefs in Canadian school children:

> Several students imagined that air was a factor in sustaining motion by 'turbulence' — swirling over the object to push it from the other side.(Kass & Lambert, 1983, p.384)

This argument was replaced in the fourteenth century by Buridan's concept of impetus: a model strongly based on Aristotelian unquantifiable categories (Nersessian, 1989, p.175; Toulmin & Goodfield, 1963, p.242). Buridan considered that the source of the incorporeal power was not in the air around a moving body, but rather, that it resided inside the body itself, and that this was responsible for the continuing motion. When it was expended, the violent motion stopped, and the object came to its proper state of rest as depicted in Figure 4-3.

Figure 4-3: Impetus model of motion assumes linear motion until impetus runs out. (McCloskey, 1983a, p.114B)

Kass and Lambert (1983) also found evidence of similar contemporary beliefs:

> Several students described motion as if the body lost energy or momentum as it moved, that is, as if motion was self-expending. (Kass & Lambert, 1983, p.384)

diSessa, in relating the concept of impetus to the presence of a set of naive p-prims[8] that encompass the various observations that inform the development of an impetus model comments:

> ...Because it does not originate in the ball. children see agency in terms of something that is transferred to it. Naive p-prims having to do with substance and transfer approximate the state of affairs ... by reifying the quality of motion (roughly, its direction and magnitude), as a restricted kind of life. In children we might call this 'animism'. Physicists call it 'momentum'. (diSessa, 1988, p.55)

8. essentially un-interpreted phenomenological observations such as: sticks float, stones sink.

Watts (1981) noted that children frequently associated motion with the presence of a force. Today this notion is perhaps subliminally reinforced by the frequent, widespread use in television sports commentary of phrases such as ...

> When he hits it, it sure stays hit![9] (Lawry, 1999)

Such expressions, while clearly in the vernacular, potentially give the impression that a propulsive 'something' (impetus), has been imparted to an object by a bat (in this case) and that it is responsible for the motion until it runs out. Describing this in terms of the Newtonian model, the ball receives an impulse from the bat, which produces a change in the ball's momentum, Δp (which in this example is *observed* as a change in velocity) in accordance with equation 4-2:

Equation 4-2 Newtonian relationship between impulse, force, and time.

$$\Delta \mathbf{p} = \int(\mathbf{F}(t) \cdot dt)$$

The resulting motion of the ball is simple projectile motion according to the Newtonian model (cf. Buridan above), and no active agent is transferred to the ball during the impact — as an axiom of the inertial model.

Hake (1994), however, argues that their is implicit merit in the notion of something being imparted...

> My approach, which I call 'concept substitution', is to reinforce the students' correct intuition that something is imparted to the ball by the hand, but to rename the 'something' momentum. Students can thus hold onto their intuitive ideas, but with a new name. (R R Hake, 1994)

A student holding genuine Aristotelian ideas, however, would argue that the incorporeal moving powers of the air caused the motion, and that the ball dropped

9. see also Osborne & Freyberg, 1985, p.44.

when this had been expended, whereas a student holding the more general medieval view would attribute the cause of motion to the impetus that was imparted to the ball by the bat, and which was progressively consumed in the ball's flight. Both categories of student are highly likely to have difficulty with the content of the VCE physics unit 4 course (Table 2-1 on page 20) because of its fundamental focus on force, and particularly gravitational force, as a central concept, and on Newton's clearly articulated laws of motion.

4.2.2.3 Problems with terminology

The term *Aristotelian* has been widely used to both describe Aristotle's theory of motion (e.g., Clagett, 1959; Crombie, 1952; Ross, 1956; Stinner, 1994; Toulmin & Goodfield, 1963), and to categorise students' mental models of motion as being *similar to* the Aristotelian model. The former use is historical, and the latter dates from 1980 when Champagne *et al.* used it in describing students' 'preinstructional knowledge.' (Champagne, Klopfer, & Anderson, 1980) Lythcott (1985; 1983, p.257) argues that this 'catchy label' has been widely applied, and is often used inappropriately to cases where the term is not an accurate description of the beliefs of students about motion (e.g. diSessa, 1982; Driver, 1981; Osborne et al., 1983; Pines & Leith, 1981). Wandersee *et al.* (1994) prefer an alternative description to more precisely differentiate between Aristotelian and other non-Newtonian theories — 'the overwhelming majority of students seem to hold a common sense, everyday notion that has elements, (in varying proportions) of *both* an Aristotelian and an impetus theory of motion.' (Wandersee et al., 1994, p.181) DiSessa (1982), however, adopted the adjective 'Aristotelian' to mean:

> For our purposes we use the term to mean that objects simply move in the direction you push them. (diSessa, 1982)

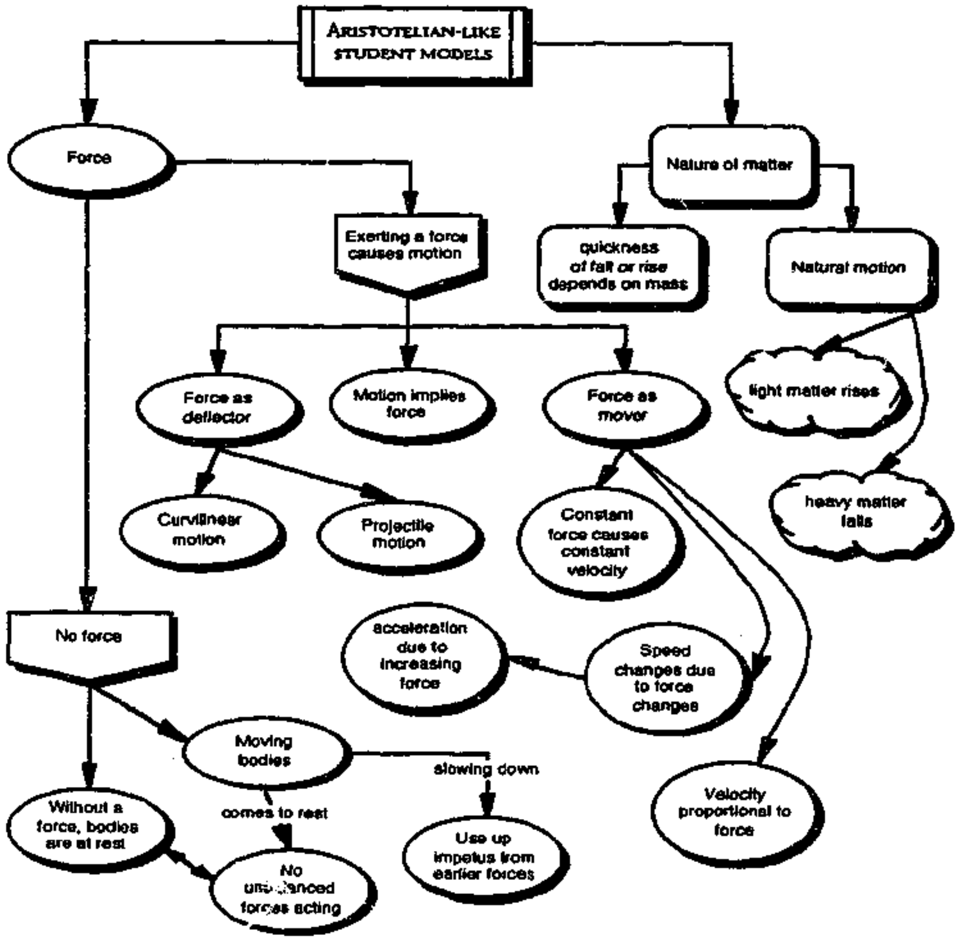
Whilst diSessa's intent is clear[10], and the issue expanded and clarified in a later work in terms of phenomenological primitives (p-prims) (diSessa, 1983, p.29-33; 1988), the cautions of Section 4.2.2.1 (a) about the problems in relating disparate paradigms have been overlooked, and the meaning *as written* is ambiguous (a point recognised by diSessa). For example, whereas Aristotle was aware that a projectile in violent motion briefly continued along its initial trajectory after its projection, and that this was a major conflict in his theory (see p.89), diSessa's use of the term could be taken to mean at least two types of motion. First, that a projectile would instantly change direction on the application of a push[11], so that a thrown object, for example, could be pushed, instantly, around a ninety degree corner with an appropriately directed push — the '*force as a mover*' (Boas, 1966; diSessa, 1983, p.30; Lythcott, 1985, p.431). Second, that an object would be deflected from its original path, but would continue in a straight line in a new direction — the '*force as a deflector*' (diSessa, 1983, p.30). These are examples of the problems that can arise from using terms out of context.

Figure 4-4 on page 95 shows examples of the potential misuse of the Aristotelian 'label' (Lythcott, 1985), in which a deeper analysis is suggested in order to get detailed understandings of the students' actual mental models. The sample serves to show how widely the Aristotelian label has been applied to particular aspects of students understanding of mechanics.

10. to the author of this thesis.

11. as described in a later work (see diSessa, 1983; Lythcott, 1985, p.431)

Figure 4-4: Components of student mental models labelled as 'Aristotelian' (after Clement, 1982, 1987; diSessa, 1982, 1993b; Hewson, 1981; Lythcott, 1985; McCloskey et al., 1980; McCloskey & Kargon, 1988; McCloskey & Kohl, 1982; McCloskey, Kohl, & Wasburn, 1981; Nersessian, 1989; Osborne, 1984; Saiyachivin, 1985; Weller, 1990, 1995; Wisan, 1977)



4.2.2.4 ARISTOTLE AND VCE PHYSICS UNIT 4

Unit 4 of the VCE course covers a wide range of phenomena that could be seen from an Aristotelian or medieval perspective. Gravity is possibly the most problematic concept, as the complete denial of its existence within this model makes it harder for students to consistently explain phenomena such as the planetary deflection, or orbital capture, of passing objects, or accelerated motion in free fall or projectile motion.

Participants in this study holding 'Aristotelian'[12] ideas of motion would exhibit some or all of the following beliefs about motion and gravity:

- A1 An object's motion is a result of its efforts to reach its natural place.
- A2 An object moves at a constant velocity that depends on the effort applied to it, and the resistance it has to overcome.
- A3 Applying a greater effort will increase a body's velocity (in a linear relationship).
- A4 Motion in the heavens simply 'is' - there is no reason for it other than that it is the object's natural state.
- A5 Motion in the heavens follows a circular path.
- A6 Satellites orbiting a planet are simply following their natural motion.
- A7 The 'slingshot' effect[13] is a result of the object falling (radially) down towards the planet to reach its proper place (no gravity).
- A8 When an object falls to the Earth, it falls at constant velocity.
- A9 Heavy objects fall faster than lighter ones (for a given resistance).
- A10 There is no force of gravity attracting objects together, nor towards the Earth.
- A11 Terrestrial motion requires the presence of an active agent (impetus).
- A12 A change of place is a process, not a change of state.

4.2.3 The Galilean theory of motion

Galileo moved the field of mechanics towards a scientific and abstract model of motion. Arons notes that Galileo developed the first correct approach to the Law of Inertia: 'rather than ask what keeps a body moving, we should ask what causes it to stop' (Arons, 1990, p.40). By a process of careful experimentation and through the use of 'thought experiments', Galileo was able to refute key aspects of the medieval model, particularly in regard to accelerated motion (including free fall), and Aristotle's laws of motion (e.g. Crombie, 1952; Drake, 1974, 1982; Naylor, 1976). These were important steps in facilitating the subsequent development of an inertial model of motion.

12. cf. cautions about the use of such adjectives as described on page 93

13. i.e., accelerating and/or deflecting a space vehicle or natural satellite by means of a close pass to a planet or other extra-terrestrial body; caused by the radial gravitational field of the planet

Figure 4-6 shows a partial concept map of the Galilean model of motion in a similar format to that used previously (p.85) for the medieval model of motion.

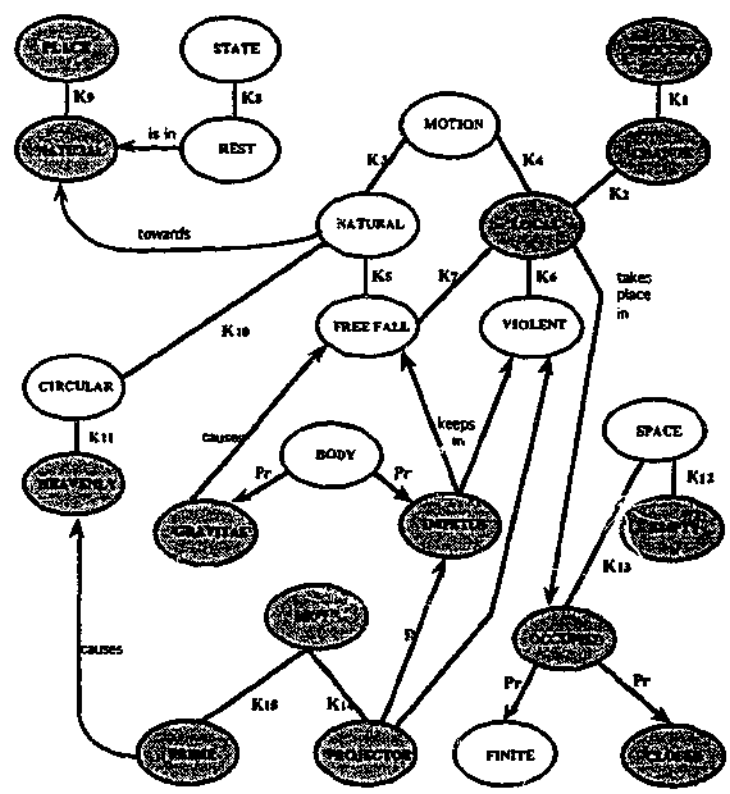
4.2.3.1 Differences from the medieval model

Much of Galileo's work focused on refining Copernican theory in terms of kinematic formulae (Hurd & Kipling, 1964, p.136). Koyré calls this process the 'mathematization of nature' — the abstraction of natural events, and subsequent development of mathematical relationships between the abstracted entities (Koyré, 1968, 1978). By abstracting and redefining a number of key entities, he built a model around quantifiable entities that were related by mathematical equations. The study of motion no longer had to be grounded in phenomenological observations and descriptions, but could be considered in the abstract (as in Galileo's thought experiments). Galileo's laws and theorems concisely summarise this model:

1. In a medium totally devoid of resistance, all bodies will fall at the same speed and during equal intervals of time, will receive equal increments of velocity.
2. *Principle of uniform motion:* an object moving on a level surface (horizontally) will continue to move in the same direction at constant speed unless it is disturbed.
3. *Principle of Superposition*: if a body is subjected to two separate influences, each producing a characteristic type of motion, it responds to each without modifying its response to the other.

In the development of this model, many Aristotelian entities that had been included on observational or phenomenological grounds were discarded as shown in Figure 4-5. The new Galilean model contained fewer entities and had a clearer theoretical basis. These changes are reflected in changes in the kind, property and relation links depicted in Figure 4-6 on page 99. As with Figure 4-2, this figure is presented here to provide the reader with a visual map of the content of the review, as well as a visual representation that allows the structural relationships within the model to be examined. The significance of the relationships and links contained in Figure 4-2 are discussed in the remainder of below.

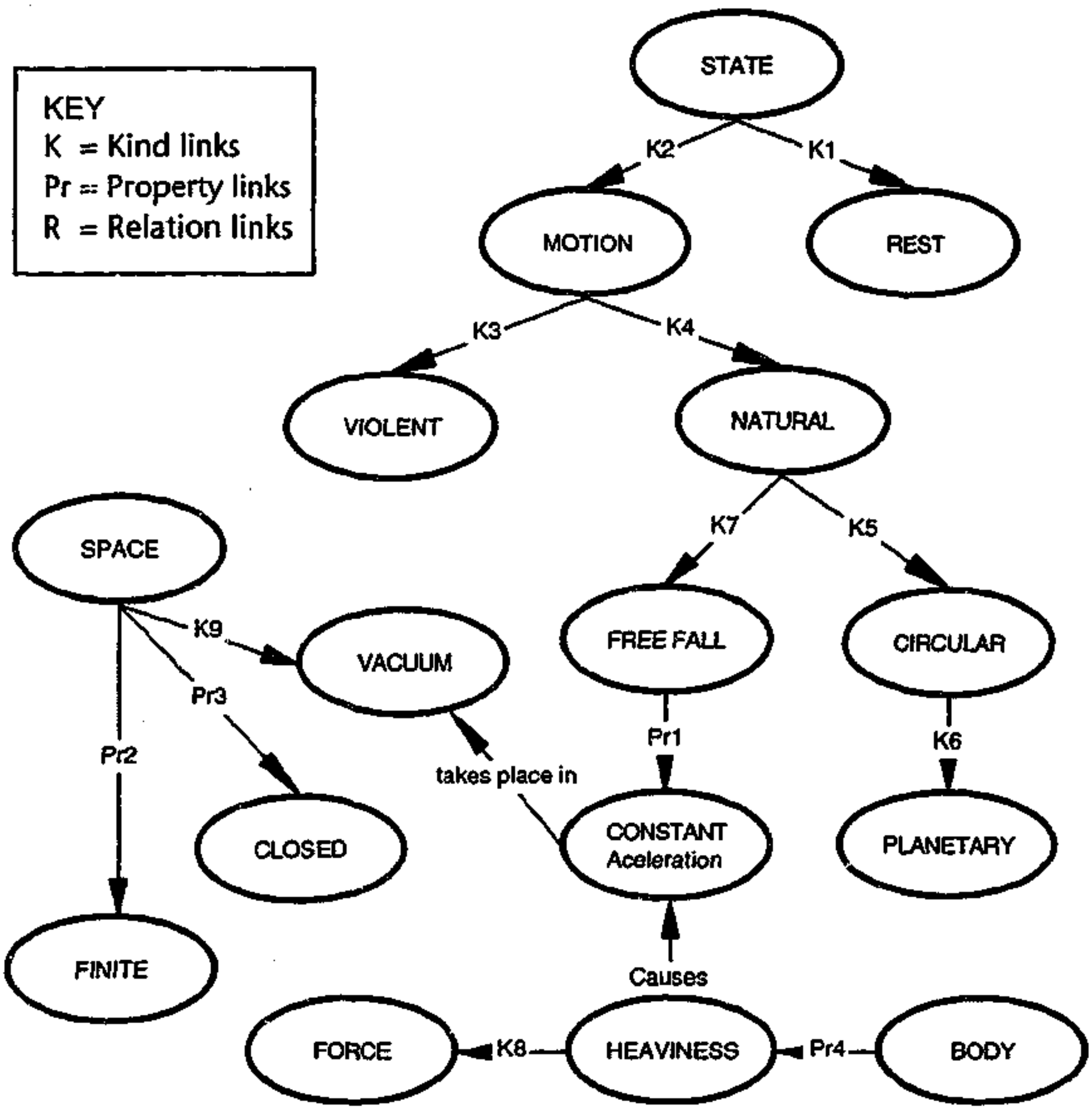
Figure 4-5: The Aristotelian entities (shaded) that are not present in the Galilean theory of motion (cf. Figure 4-2)(after Nersessian, 1989).



4.2.3.1 (a) Motion as a state

Moving and stationary objects are viewed as two different states of a body (K_1, K_2), rather than requiring different explanations for each. This allowed Galileo to study motion from a single coherent framework, and had the pragmatic advantage of allowing the study of motion on the Earth to be generalised to the astronomical works of Brahe, Kepler, and Copernicus. Experimental results on Earth-bound objects could then be used to explain planetary motion. In particular, this allowed the exploration of a major Copernican concern with the orbital motion of the Earth — why the Earth's motion did not appear to affect the trajectories of freely falling objects or projectiles on the Earth. In the absence of an inertial model, it was expected that a moving Earth would cause relative motion once the object had got free of its 'mover'[14], and that such relative motion should be obvious to an observer on the Earth (Toulmin & Goodfield, 1963, p.182-187). The failure to observe such motion was used as a strong argument against the Copernican model.

Figure 4-6: The Galilean theory of motion (after Nersessian, 1989, p.172)



14. cf. impetus in Section 4.2.2.2 (b) on page 90.

Similar classes of beliefs about impetus and curvilinear motion have often been found in college students and school children. For example, McCloskey's pioneering studies demonstrated that this is a common, and resilient belief (e.g. McCloskey, 1983a, 1983b; McCloskey et al., 1980; McCloskey & Kargon, 1988; McCloskey & Kohl, 1982; McCloskey, Kohl, & Washburn, 1981). For this reason they form one class of 'misconception' explicitly probed by the FCI (Hestenes & Wells, 1992; Hestenes et al., 1992)[15].

4.2.3.1 (b) Natural and violent motion

Galileo redefined the meaning of the terms natural motion (K_3) and violent motion (K_4) to mean motion that happens by itself e.g., free fall, and motion that requires an agent. By viewing motion as a state rather than a process, by removing Aristotle's distinction between local and heavenly motion (p.100), and by providing a functional definition that facilitated experimental investigation, he opened the way for the development of an inclusive model of motion that was not reliant on the structure of the heavens: an essential precursor to the development of an inertial model of motion, as it decouples motion from the space in which it moves.

4.2.3.1 (c) Force

A focus on kinematics, rather than on dynamics, as the basis of supporting the Copernican model, appears to have affected Galileo's thinking in several ways (Hurd & Kipling, 1964, p.136). In particular, he kept the medieval notion of 'heaviness' as an intrinsic property of a body[16] (Pr_4), rather than it resulting from

15. see Section 6.3 on page 187.
16. cf. "Gravitas" in the medieval model (page 89).

an interaction with some external agent, and even though he frequently refers to 'gravity', it is not the cause of 'heaviness' which is a type of force (K_8). Galileo initially described the motion of a projectile as an interaction between force, weight, gravity, and three types of impetus - 'outside', 'impressed', and 'opposing', before producing a simplified and more coherent model based on the acceleration of falling bodies (Hurd & Kipling, 1964, p.167).

4.2.3.1 (d) Falling bodies

Galileo showed that constant acceleration caused by heaviness (a 'kind' of force — K_3) was a property of all freely falling objects (Pr_1) (cf. Holton et al., 1968, p.53-5). He demonstrated that the constant, uniform acceleration of a falling body would only happen in a vacuum, thus overthrowing Aristotle's rejection of its existence. A vacuum (K_9) therefore became possible in nature. This was an important step in the development of an inertial model of planetary motion because it allowed objects to move without the constraints of Platonic structures or other physical constraints. Curiously he kept the Aristotelian notion of space as finite and closed (Pr_2, Pr_3) because of his belief in the Copernican cosmological model with its core assumption of circular planetary orbits (K_5, K_6), even though he was presumably aware of Kepler's three laws of planetary motion, and their origins in elliptical orbits (Arons, 1990, p.41; Hurd & Kipling, 1964, p.135).

He also demonstrated that in the absence of frictional forces, any object would keep moving after any propulsive forces had been removed from it (Hurd & Kipling, 1964, p.163) — an experimental result that formed the basis of his theory of motion and thoroughly discredited Aristotelian theory. However, he did not formulate the concept of inertia from his findings. This was left for Descartes to develop, and for Newton to subsequently employ in his theory of mechanics (Toulmin & Goodfield, 1963, p.248).

4.2.3.2 GALILEO AND VCE PHYSICS UNIT 4

Those participants in this study who hold 'Galilean' ideas of motion would exhibit some or all of the following beliefs about motion and gravity:

G1 In the absence of resistance, the natural motion of a falling body is continuous acceleration.

G2 The distance travelled per unit time by a body falling from rest is in proportion to the ratio of odd numbers starting at unity.

G2 Projectile motion can be described in terms of two independent motions, at least one of which may be accelerated motion.

G3 'Heaviness' is an intrinsic property of a body, and is not due to gravity.

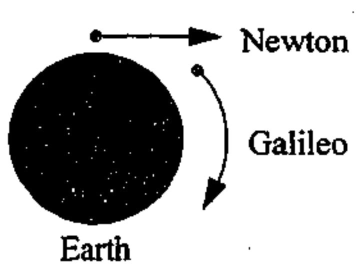
4.3 The Newtonian model

In accordance with the structure of this review, this section summarises the key developments of Newtonian mechanics from its Galilean origins. More extensive accounts can be found in Eisenbud (1958), Clagett (1959), Project Physics Committee (1972), and Hurd (1964). Figure 4-8 (on page 105) is provided as a visual map of the content of this section of the review, as well as a visual representation that allows the structural relationships within the model to be examined. The significance of the relationships and links contained in Figure 4-8 are discussed below.

Newton's fundamental changes to the Galilean model were to focus on dynamics, and to develop a model of motion based on, and *limited in scope by*, the use of constant-separation-velocity inertial reference frames[17] (Halliday, Resnick, &

Walker, 1997a, p.66-70). This radical conceptual restructuring resulted in a universal, fully abstracted and mathematized model that overcame Galileo's difficulties with impetus and force[18], and that, in conjunction with the development of calculus, allowed the solution of complex kinematic and dynamic problems. Newton's model is succinctly described by his three laws of motion (Section 4.3.1). Newton's inertial model was fundamentally different from Galileo's notion of bodies continuing to move in a straight line; Galileo was thinking of an object moving along (around) the Earth's surface, but Newton's model demanded motion along a 'absolute' straight line[19] as in Figure 4-7.

Figure 4-7: Newtonian and Galilean models of linear motion. (after Holton et al., 1968, p.74)



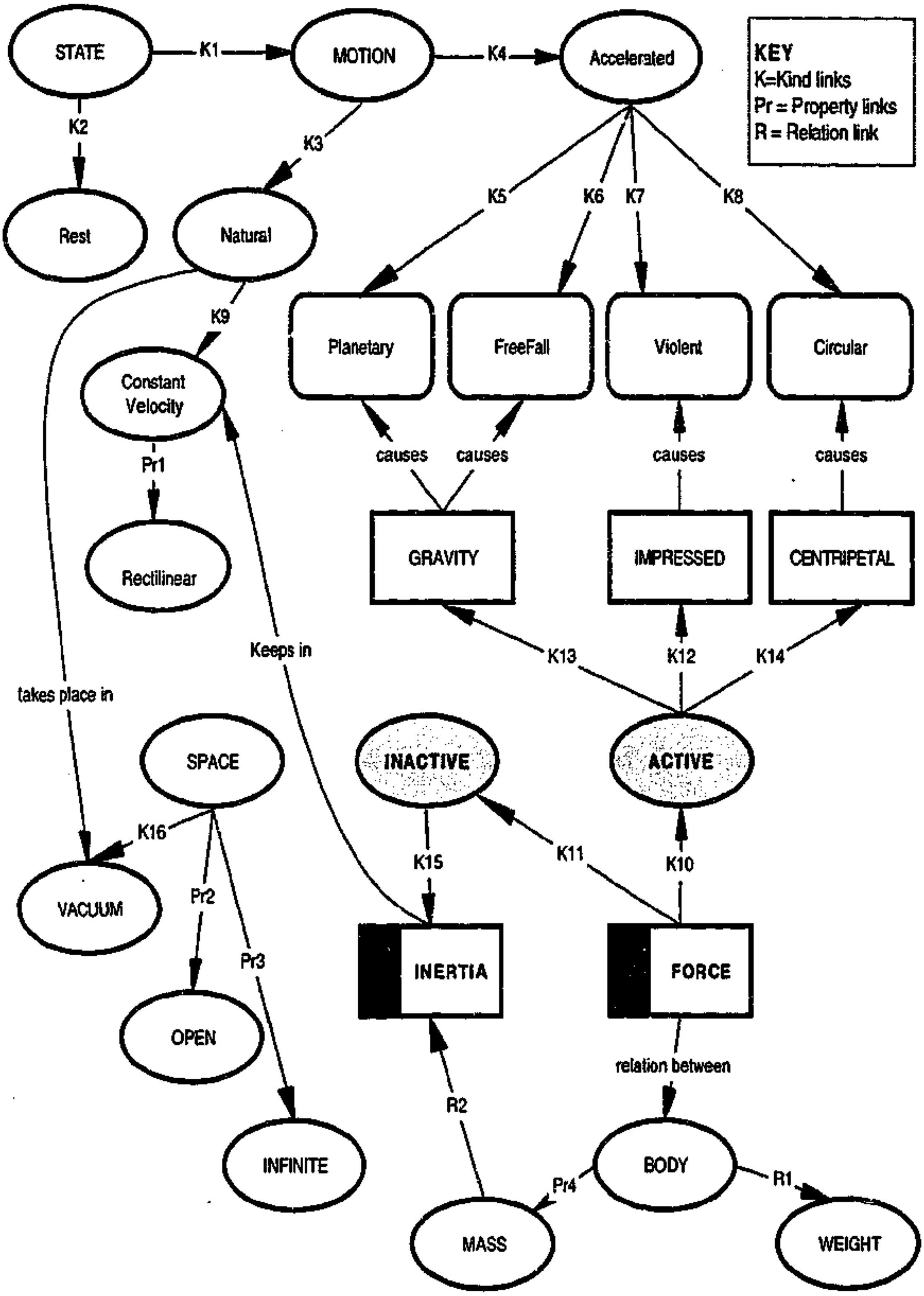
Confusion over inertial versus non-inertial reference frames may be a hindrance to students who confuse acceleration *within* an inertial frame, such as a body falling under gravity, or undergoing rotational motion, with the acceleration of a reference frame itself, or motion at relativistic speeds, where Newtonian physics does not apply (Armstrong, 1984; Casanova & Mendialdua, 1997; Czudková & Musilová, 2000; Galili, 1996, p.224; Halstead & James, 1984; Lotze, 1995; Mendialdua, 1997). In many physics texts, this important qualifier is often stated in the

17. i.e, reference frames that move at constant velocity, referred to here as 'inertial frames'.
18. cf. Section 4.2.3.1 (c) on page 100.
19. in normal Newtonian contexts as opposed to relativistic effects and space curvature.

introduction, but is not emphasised elsewhere. However, Hake's 'Socratic Dialogue Labs' (1998a) explicitly emphasises it in conjunction with the definitions of Newton's laws (Hake, 1998b, p.51; 1998c, p.44).

As shown in Figure 4-8, motion and rest (K_1, K_2) remain as states, differentiated only by the latter having zero velocity. Motion is no longer divided into 'natural' and 'violent' categories: natural motion (K_3) is redefined to mean the motion of a body in a vacuum at constant velocity. Force becomes a unifying cause of all types of motion. In this model, objects axiomatically maintain a state of uniform motion unless acted on by an external force. Inertia (measured by its mass - R_2) is responsible for keeping a body moving at a constant velocity (K_9. K_{15}), but not as some form of impetus — in Figure 4-8 this is represented as an 'inactive' force (K_{11}), as a way of representing that inertia keeps bodies in motion (at constant velocity) without the presence of an 'active' force. The term 'active' force is used to describe *normal* Newtonian force (K_{10}) — i.e., that which causes a body to *accelerate* (K_{12}, K_{13}, K_{14}).

Figure 4-8: The Newtonian model of mechanics. (after Nersessian, 1989, p.173)



Violent motion (K_7) is one component of the more inclusive category of 'accelerated' motion (K_4), along with circular motion (K_8), planetary motion (K_5), and free fall (K_6); areas that had troubled both Aristotle and Galileo. Circular motion results from a centripetal force (K_8,K_{14}), and planetary motion and free fall are consequences of gravity. Newtonian Force has become the key organising element, relating gravity, centripetal force, and impressed force to a range of contexts–planetary motion, violent motion, circular motion, and free-fall.

Gravity was recognised as a kind of force (K_{13}) that was different from 'heaviness', allowing a differentiation between mass (a property of a body - Pr_4), and weight (related to mass - R_1) to be recognised (Galili, 1996, p.222). This was a critical conceptual step as it allows for the possibility to have a body with no gravity acting on it — which is a *prerequisite* for an inertial model of motion. Weight was defined in operational terms as the 'pressing influence (i.e. contact force) due to gravity of the bodies being in contact' (Galili, 1996, p.224). This distinction was lost in the common use of the term 'weight', causing conceptual difficulties for physics teachers and students (Bar et al., 1994; Galili, 1993, 1995; 1996, p.224; Graham & Berry, 1993). Newton's law of universal gravitation allowed a single theory of mechanics to apply to both the Earth and the Heavens.

> Newton's main contribution was to emphasise the universality of his laws, and yet 'to bring them down to Earth'. (Watts, 1982,p.115)

To accommodate the demands of his inertial model, space had to be infinite and open (Pr_2, Pr_3) and a vacuum (K_3,K_{16}) was axiomatic.

4.3.1 *Newton's laws of motion*

The Newtonian concept of Force lies at the heart of the Newtonian model of mechanics. Its pre-eminence is dictated logically by Newton's three fundamental laws which define the properties of a (Newtonian) conservative system within an inertial frame. Motion and rest remain as states (K_1, K_2): the concept of uniform motion applies to both, indicating zero nett force. Inertia (R_2) is a property of all objects and is related to mass. 'Natural' motion is reconceptualised as uniform inertial motion (K_3, K_9).

4.3.1.1 Newton's First Law

Newton redefined force from being a 'mover'[20] and a property of a body, to an 'accelerator' that was an abstracted, functional quantity that explained changes in motion as expressed in his first law of motion:

> If no force acts on a body, we can always find a reference frame in which that body has no acceleration. (Halliday et al., 1997a, p.82)

The significance of inertial and non-inertial frameworks is often overlooked in school physics teaching (e.g., Casanova & Mendialdua, 1997; Czudková & Musilová, 2000), where Newton's first law of motion is commonly stated as:

> Consider a body on which no forces act. If the body is at rest, it will stay at rest. If the body is moving with constant velocity, then it will continue to do so. (Halliday et al., 1997a, p.82)

20. cf. the Aristotelian model in Section 4.2.2.2 (b) on page 90

4.3.1.2 NEWTON'S SECOND LAW

Whereas the first law (p.107) described a state of no nett force, the second law of motion describes motion in the *presence* of external forces acting on a body:

> The acceleration of any object is inversely proportional to its mass and directly proportional to the resultant force acting on it. (Chan, Nicholson, Urquhart, & Wilkinson, 1991, p.182)

This is usually represented by the simple *vector* equation:

Equation 4-3 Newton's second law: mathematical form.

$$\sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$$

4.3.1.3 NEWTON'S THIRD LAW

The third law describes the relationship between action-reaction pairs of forces. This is an important aspect of the model, as it dispels any Galilean-type confusion about types of forces and modes of action:

> Forces always occur in pairs. If a body, *A*, acts on a body, *B*, an equal and opposite force is exerted by body *B* on body *A*. (Chan et al., 1991, p.183)

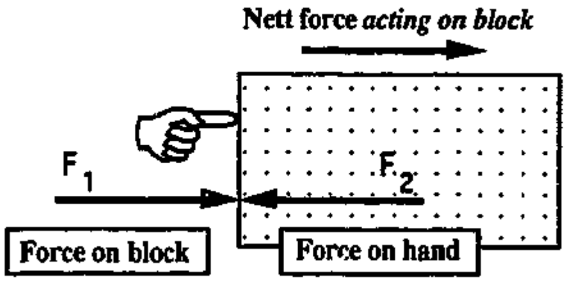
This is represented mathematically by the vector equation:

Equation 4-4 Newton's third law.

$$\vec{\mathbf{F}}_{ab} = -\vec{\mathbf{F}}_{ba}$$

Students are often confused as to why the two forces do not cancel, preventing motion from occurring (Brown & Clement, 1987; Gauld, 1993, 1998; Halliday et al., 1997a, p.90). To overcome this confusion, Halliday et. al. (1997a) suggest that the fact the two forces act on two different bodies needs to be clearly stated, and the origin of the force-pair clearly differentiated as in Figure 4-9. Confusion about vectors, and common classroom scalar treatments of problems ($|F_1| = |F_2|$) are also a potential source of confusion for learners.

Figure 4-9: The nature of 'equal and opposite' forces in Newton's third law.



Further problems for students arise from the Newtonian 'action at a distance' model, and its implied instantaneous generation of an equal and opposite force, as there are circumstances where this does not happen, and the third law does not hold *instant by instant*[21] (Arons, 1990, p.67). Roach (1992) notes that students often confuse the forces with momentum, and tend to view force as a property of single objects rather than as a relationship between two objects.

4.3.2 Newton's law of universal gravitation

Newton postulated the existence of a universal attractive *gravitational* force between matter — every particle attracts every other particle with a gravitational force of magnitude F_g that decreases in an inverse-square relationship with distance, **r**, given by Equation 4-5[22]:

21. e.g., using a long elastic rod to push on a second object: elastic deformation along the rod to the end is not instantaneous and there is a delay until the force is actually transmitted to the second object. N3 however holds instant by instant for the forces between the deforming 'slice' of the rod and the 'slices' adjacent to it.

Equation 4-5 Magnitude of the gravitational force between particles.

$$|F_g| = G\frac{Mm}{r^2}$$

All particles of matter are surrounded by a radially-directed gravitational field. The gravitational acceleration, a_g, at radial distance, r, due to a single mass is therefore:

Equation 4-6 Magnitude of the gravitational acceleration caused by a single particle.

$$|a_g| = \frac{GM}{r^2}$$

The principle of superposition and integration by parts allows the calculation of the gravitational force produced by real objects, provided that the size of the interacting masses are small compared to their distance apart. The Shell theorem (Halliday, Resnick, & Walker, 1997b, p.328) simplifies such calculations in the case of spherical objects, allowing them to be treated as point masses located at their centre. This is an essential aspect of the VCE physics curriculum where it simplifies calculations by allowing students to approximate planets and satellites to spheres.

4.3.2.1 KEPLER'S LAWS OF PLANETARY MOTION

Newton was able to show that his law of gravitation could explain Kepler's empirical equations that described the motion of the planets (Halliday et al., 1997a, p.334). They are included here because of their fundamental importance to the VCE context that this study examines, and their underpinning by Newton's gravitational law. They have been included in the data-analysis framework (see Section 4.4.3 and Section 5.8z) as a sub-category of the Newtonian model:

22. G is Newton's Gravitational constant = 6.67×10^{-11} $N.m^2/kg^2$

K1 All planets move in elliptical orbits with the Sun as their focus.

K2 A line that connects a planet to the Sun sweeps out equal areas in equal times.

K3 The square of the period of any planet is proportional to the cube of the semi-major axis of its orbit.

4.3.3 Newton and VCE physics unit 4

The 'Newtonian' student will use the following laws as the basis of explanations of dynamic phenomena:

N1 If no forces act, a body at rest will stay at rest, and a body moving with constant velocity will continue to do so.

N2 The acceleration of any object is inversely proportional to its mass and directly proportional to the resultant force acting on it.

N3 Forces always occur in equal and opposite pairs.

N4 The gravitational force between two objects varies with the product of their masses, and inversely with the square of their distance apart.

These categories form the basis of the Force-Concept Inventory instrument (Hestenes et al., 1992) that is employed in this study in an attempt to determine the participants' use of Newtonian models in solving mechanics and dynamics problems.

4.4 Relevant mechanics 'misconceptions'.

In the terms of this study, misconceptions are aspects of mental models of mechanics that are discordant with the Newtonian model. Selected research of relevance to this study is reviewed below under the categories of gravity (Section 4.4.1), falling and curvilinear motion (Section 4.4.2), and orbital motion (Section 4.4.2.1) as these embrace the major contexts of the VCE physics curriculum. Some of the research reviewed here overlaps, as expected, with aspects of the historical models of mechanics.

In this section, aspects of selected research related to gravity is presented from these different perspectives in order to emphasise particular aspects of relevance to this study. The diagrams that form the focus of the discussion may contain similar details, and particular research papers are common to some, but each diagram presents a different emphasis.

In this section, selected studies are reviewed to raise key issues in the relevant areas. These are then combined with findings from other studies and presented graphically in order to focus on the kinds of items that are used to form the content-knowledge indicators for the subsequent data analysis phase of this thesis.

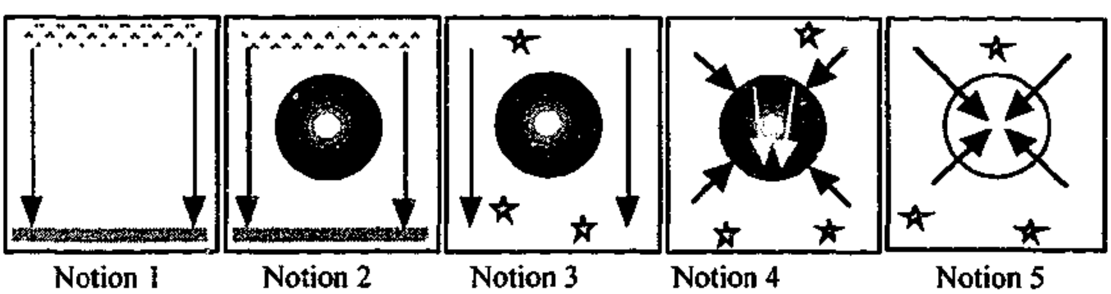
4.4.1 Gravity

Gravity, as such, has not been a major focus of misconceptions research, with comparatively few studies focusing explicitly on it compared to those on other aspects of Newtonian mechanics (e.g., Ameh, 1987b; Ameh & Gunstone, 1986; Galili, 1995, 1996; Gunstone & White, 1981; Roper, 1985; White, 1990). Only 30 (≈0.6%) of the 5206 entries in the IPN misconceptions database use 'gravity' as a descriptor or in a title (Duit & Pfundt, 2000).

Early research into the learners' understandings of gravity (e.g., Champagne, Klopfer, & Gunstone, 1981; Gunstone & White, 1981; Kass & Lambert, 1983; Osborne, 1981; Selman, Krupa, Stone, & Jaquette, 1982; Stead & Osborne, 1980; Watts & Zylbersztajn, 1981) revealed the that while learners often hold clear phenomenological positions about gravitational events, they do not necessarily hold causal models that can be used to generate coherent explanations about the effects of gravity *across a range of contexts and problem types*. The studies revealed that learners often hold an extensive set of erroneous, contradictory, and inconsistent ideas about gravity — as is common with other areas of Newtonian mechanics.

Nussbaum and Novak (1976) used structured interviews to investigate second grade childrens' understanding of 'Earth concepts', including gravity, in science lessons. In conjunction with a subsequent cross-age study, proposed a five-stage developmental model of childrens' understandings of Earth concepts; the 'Earth Notions' classification scheme as in Figure 4-10, proposing that children move from a flat-Earth model, where gravity is oriented to the surface, to a more realistic spherical model in which gravity is directed towards the Earth's centre (Nussbaum, 1979; White, 1990, p.8).

Figure 4-10: Nussbaum's Earth Notions developmental stage model (Nussbaum, 1979)



The Earth notions depicted above are:

1. The Earth is flat.
2. The Earth is shaped like a ball surrounded by space. We live on the flat part of the ball.
3. The Earth is shaped like a ball surrounded by space. We live on the top of the ball.
4. The Earth is shaped like a ball surrounded by space. People live all around the ball. Things fall to the surface of the Earth.
5. The Earth is shaped like a ball surrounded by space. People live all around the ball. Things fall to the centre of the Earth.

A number of similar studies have been undertaken in several countries (Arnold, Sarge, & Worrall, 1995; Chae, 1992; Mali & Howe, 1979; Maria, 1993; Sneider, Pulos, & Freenor, 1986; Sneider, Pulos, Freenor, Porter, & Templeton, 1983; Sneider & Ohadi, 1998; Vosniadou & Brewer, 1989, 1990). A study of Nepalese children returned similar results, but identified a four year delay in attaining similar levels on the model; a difference attributed to school resourcing and cultural factors (Mali & Howe, 1979). Sneider and Pulos (1983) developed a three-point gravity scale and a four point Earth-shape scale (Table 4-1) in order to better differentiate between students' understanding of gravitational concepts, and their understandings of the Earth as a body in space. They reported that students usually reach level three of the gravity scale by the seventh or eighth grade, and that the developmental sequence, considering the acquisition of both Earth and gravity concepts, follows a different sequence than that inferred from Nussbaum's composite scale.

Table 4-1: Earth shape scale and gravity scale (Sneider et al., 1983)

Earth shape scale	Gravity scale
1 The Earth is flat	1 Objects fall towards an absolute down in space
2 People live on the flat parts of the Earth;	2 Objects fall towards the surface of the Earth
3 People live all on top of a ball shaped Earth;	3 Objects fall towards the centre of the Earth.
4 People live all around a ball shaped Earth	

Stead and Osborne (1980) investigated school students' views about gravity by requiring them to determine if gravity was present or absent in eight different physical situations. The students were found to believe that:

- Gravity changes with height, but not as according to Newtonian theory.
- Gravity doesn't exist in space (including the moon).
- Gravity is caused b[illegible] pushing down on objects.
- Gravity is responsible for both reaction forces and buoyancy forces.
- Gravity is result of the Earth's axial rotation.
- Weight and the force of gravity are different.

A number of subsequent studies of school childrens' beliefs about gravity (e.g., Chae, 1992; Maria, 1993; Sneider & Ohadi, 1998; Vosniadou & Brewer, 1989, 1990) identified further beliefs, some of which were similar to those above, but also many subtly different, or contradictory beliefs about gravity. Other studies commonly explored problem solving approaches that required students to apply force and gravity concepts to specific contexts (e.g. Champagne et al., 1981; Gunstone, 1987; Gunstone & White, 1981). Even with increasingly widespread public knowledge of Space[23], young children retain many of these ideas (e.g., Chae, 1992; Maria, 1993; Pirkle & Pallrand, 1988). Gunstone and White (1981) investigated first-year university physics students (n=170) knowledge of gravity using a 'predict-observe-explain' protocol (Champagne, Klopfer, & Anderson, 1979) to explore eight gravitational contexts. Whilst finding similar *types* of outcomes to those identified previously, they particularly noted:

- a lack of ability to explain a prediction;
- a frequent lack of 'common sense' in arguments about gravity;
- the inappropriate use of mathematical arguments;
- the decontextualisation of student knowledge (not being able to relate to 'real world' situations);
- errors of scale (related to the previous point) affected the validity of arguments.

23. as gleaned from US and Soviet space programs, print, visual, and electronic media.

In a study of school students' understandings of gravity, Watts (1982; 1981) identified eight conceptual frameworks held by students:

- Gravity is a force that requires a medium to act through.
- Where there is no air there is no gravity.
- Gravity increases with height.
- Gravity is constant — moving objects try, and fail, to 'counteract' gravity.
- Gravity begins to operate when objects start to fall down, and continues until they are at rest on the ground.
- Gravity is a large force. - students' sense of gravity is unrelated to either the range or quantity of matter involved; rather it is large because it has so many objects to act on.
- Gravity is selective - it does not act on all things in the same way at all times.
- Gravity is not weight - but can act in conjunction with it to hold things down.

These categories suggest confusion over the nature, mechanism, and effects of gravity. Minstrell (1994) notes that such confusion in the ontological and relational aspects of physics concepts may be due to unresolved and unformed links between 'scraps' of factual understanding and conceptual development, so that the effects of gravity are not abstracted from its phenomenological manifestations. McCloskey (1982) effectively supports this view, noting that while most people have an accurate knowledge about the behaviour of moving objects, they don't necessarily make effective use of their knowledge in discussing new or abstract problems. The belief that gravity only acts during falling, and not on rising objects suggests confusion between gravity as a force, and as a causal explanation for falling as in the example of *The Simpsons* discussed previously[24]. Similarly, students reported the presence of a 'forward' impetus-like force that moving objects used to 'overcome gravity' (cf. Aristotle). The presumed increase of gravity with height

24. See page 18

perhaps also arises from a phenomenological description of projectile motion - with the apogee (arguably the most obvious visible aspect of gravity's effect) occurring at the highest point. Watts suggests that students think that the increasing gravity experienced by rising objects eventually overcomes the object, causing it to fall, and that it is related to the notion that some students think that higher objects require larger forces to support them than do lower objects. Likewise, the belief that gravity requires a medium may perhaps be indicative of an emerging awareness of, or need to understand, action at a distance effects.

Vosniadou (1992; 1990; 1992) examined children's and adults' knowledge of observational astronomy, identifying three categories of mental models — intuitive, synthetic, and scientific, that were used in explaining astronomical events. Vosniadou (1992) suggests that '...as children develop and are exposed to scientific explanations of these phenomena they move from intuitive mental models based on their experience and showing no influence from adult scientific models to synthetic models that are a combination of intuitive and scientific views.' These categories map loosely on to Nussbaum's stages, where development is assumed to move from a scientifically uninformed view, to a 'correct' scientific view. Vosniadou argues that the shift between the categories (flat Earth to sphere) involves significant changes between conceptually inconsistent knowledge systems — a point made earlier in regard to the 'shift' between historical models. (p.81)

Ameh (1987a; 1987b; 1986), noting that scant attention to role of the teacher was evident in science education research, explored teachers' and students' conceptions of lunar and terrestrial gravity, finding significantly different misconceptions[25] between the teacher and student populations. Ameh argues that because the teachers' misconceptions were rarely found in their students, the teachers were compensating for their lack of knowledge by the increased use of external resources such as student textbooks. The students' ability to articulate their misconceptions improved with their year level, shifting from naive understandings related to air and pressure in Year 9 students (≈14-15 years), to more articulate, but incorrect explanations in Year 11 (≈16-17 years).

Piburn (1988) found that while most of the college students studied held some understanding of the relationship between the mass and gravity[26] of an object, they were uncertain about its nature and action. Many believed that larger planets would have lower gravitational field strengths on their surface because of the greater radial distance from their centre, where gravitational force acted from, and failed to consider that the increased mass (of larger planets) would result in higher gravitational field strengths at the surface.

The research and professional literature demonstrates that students' understanding of gravity, viewed both as a specific example of a Newtonian force, and as a general phenomenological construct for explaining falling, weight and projectile motion, is poorly understood by school children (e.g., Bar et al., 1997; Czudková & Musilová, 2000; Hártel, 2000; Oliva, 1999; Robertson, 2000; Sneider & Ohadi, 1998). There is frequent confusion over the effect of gravity on moving objects, with students commonly unable to differentiate between cause and effect, action-at-a-distance, whether it acts equally on all types of objects in all cases (e.g. Earth - Moon), how and why weight varies, and whether it actually exists in space (e.g., Bar et al., 1997;

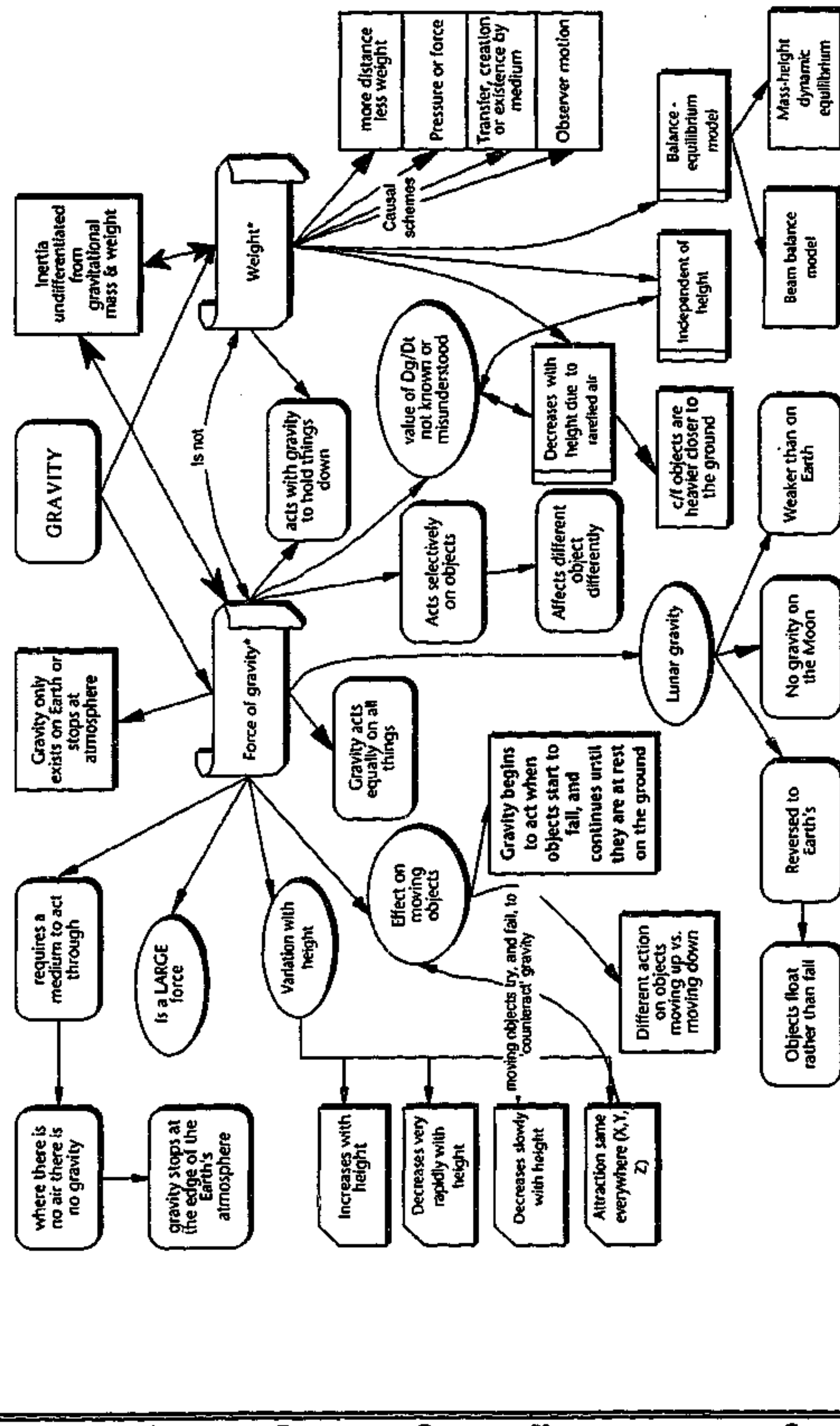
25. the term used in the relevant texts

26. meaning the gravitational field strength produced by a mass

Eckstein & Shemesh, 1993; Galili, 1993; Minstrell & diSessa, 1994; Robertson, 2000; Sneider & Ohadi, 1998; Treagust & Smith, 1989).

Figure 4-11, developed from a selection of representative literature, shows major aspects of learners' conflicting and erroneous beliefs about gravity and related concepts. Subsequent figures illustrate selected aspects of learners' understandings of gravity from a number of perspectives. From the disparate range of often inconsistent and conflicting ideas presented below, a number of key aspects of relevance to this study can be identified and used to develop categories that can be used in categorising the responses of the participants of this study (see Section 5.8).

Figure 4-11: Components of students' understanding of gravity (after Ameh, 1987a, 1987b; Ameh & Gunstone, 1986; Arnold et al., 1995; Bar et al., 1997; Bentley & Watts, 1989; Dawson & Rowell, 1993; Eckstein & Shemesh, 1993; Graham & Berry, 1993; Gunstone & White, 1981; Minstrell, 1982; Minstrell & diSessa, 1994; Nelson, 1991; Paras, 1990; Robertson, 2000; Sneider & Ohadi, 1998; Stead & Osborne, 1980; Treagust & Smith, 1989; Trumper & Gorsky, 1996; Watts, 1982).

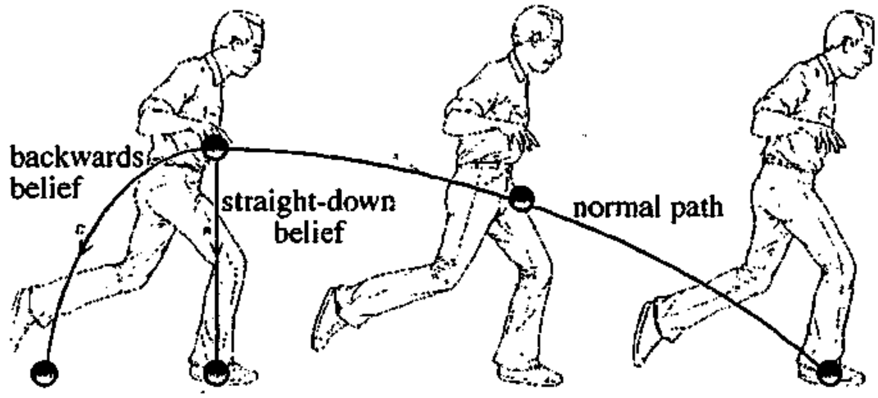


4.4.2 Falling, curvilinear and orbital motion

McCloskey (McCloskey et al., 1980; McCloskey & Kohl, 1982; McCloskey, Kohl, & Wasburn, 1981) examined aspects of students' knowledge of falling and curvilinear motion, finding that many held naive[27], systematic and medieval (impetus) views of motion (McCloskey, 1982, 1983a, 1983b). Their impetus-model underpinned three common categories of misconceptions: the straight-down belief (McCloskey, Kohl, & Wasburn, 1981), the curvilinear impetus belief (McCloskey & Kohl, 1982), and resistance to gravity (McCloskey, 1982).

1. The 'straight-down' belief - the notion that any falling object will fall directly to the ground regardless of its initial velocity, was attributed to students' difficulties in discriminating between motion viewed from different frames of reference and a concomitant reliance on a personal frame of reference[28]. The 'backwards' belief has the same origin.
2. An impetus-like property kept objects moving in a curved path when no longer mechanically constrained to do so (McCloskey et al., 1980; McCloskey & Kohl, 1982).
3. The effects of gravity could be partly overcome by an object's impetus-like properties (McCloskey & Kohl, 1982).

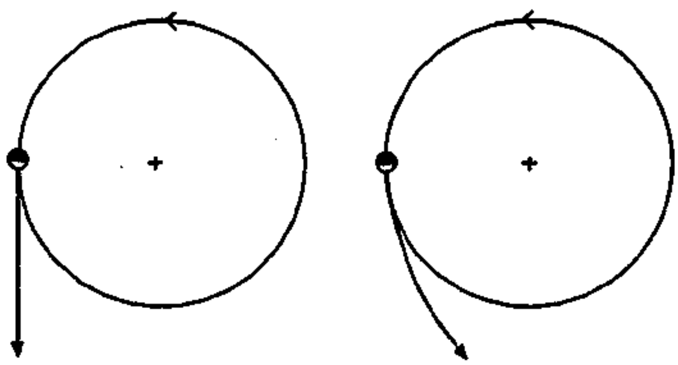
Figure 4-12: The straight-down belief and backwards belief (McCloskey, 1983a, p.114A).



27. later referred to as 'intuitive' understandings (McCloskey, 1983a)
28. i.e., relative to their own motion.

The circular impetus belief is based on the belief that a circular impetus is imparted to a rotating object, such that if the object breaks free of its constraints, it will continue to move along a curve path as in Figure 4-13. Students have applied these misconceptions to a large number of contexts, and as a result, they have been included in the FCI and are, arguably, as useful as the 'Aristotelian' label in describing a large number of findings.

Figure 4-13: Circular impetus belief (right) compared to the Newtonian model (left) (after McCloskey, 1983a, p.120).



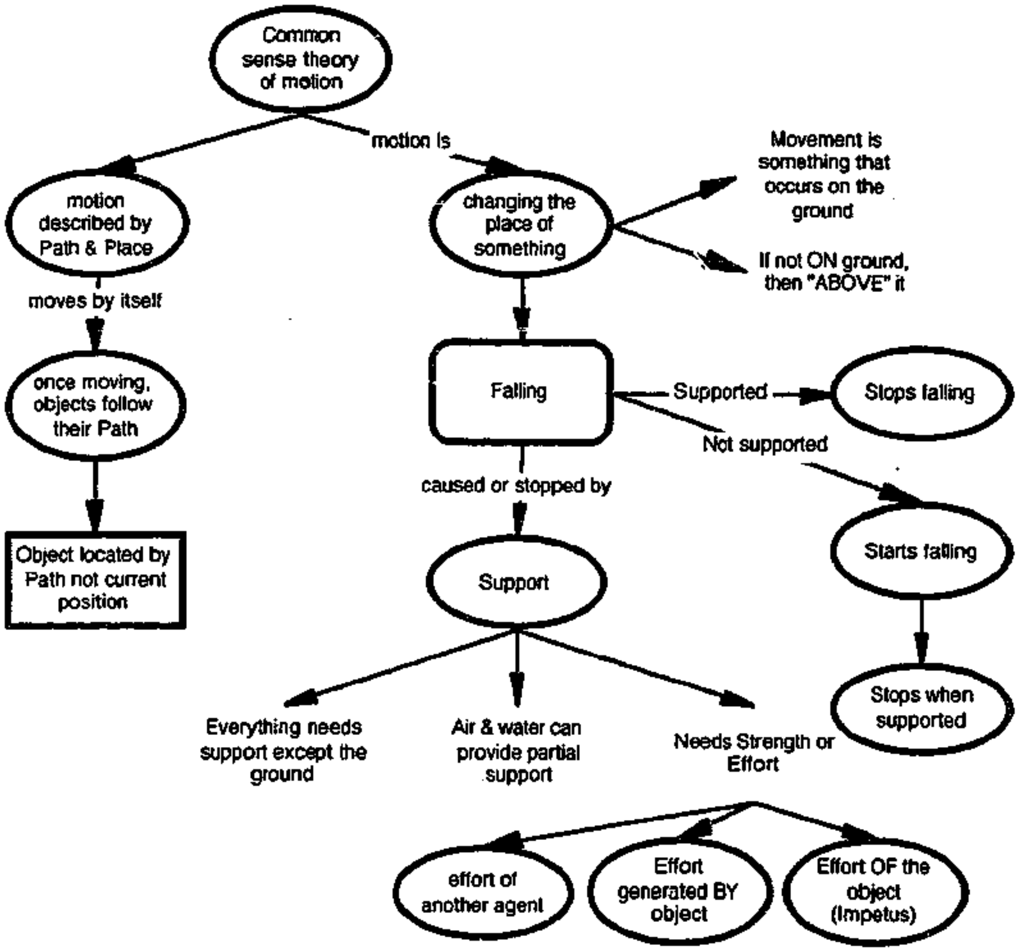
Graham and Berry (1993), noting Roper's (1985) concern about senior students' understandings of gravity (cf. Montemayor, 1999), showed that the assumption that senior students have an intuitive or functional understanding of gravity is unrealistic. Students were questioned about the time it takes two balls of different mass to reach the Earth's surface, and what would happen if they were to

do this on the Moon. Five categories of responses were identified:

1. The balls would fall simultaneously, but time would be longer on the Moon.
2. The balls would fall simultaneously, but no mention of differences on the Moon.
3. Correct response on Earth, but expecting the heavier ball to land first on the Moon.
4. The heavier ball will fall first in both situations, but take longer to fall on the Moon.
5. The heavier ball would land first on Earth, but the balls would land simultaneously on the Moon.

Bliss (1989) builds on Haye's (1979) framework of 'everyday knowledge' to describe a model of motion based on 'support and falling' (Figure 4-14) that has strong similarities to the Aristotelian model.

Figure 4-14: Support and falling model (after Bliss, 1989).



Galili (1993; 1995; 1996) likewise demonstrated that learners hold complex and confused understandings of weight, and its relationship to gravity and gravitational force. Table 4-2 lists the operational conceptual schemes of weight identified in students by Galili et.al. (1996, p.231).

Table 4-2: Operational schemes about weight held by students (Galili, 1996, p.231).

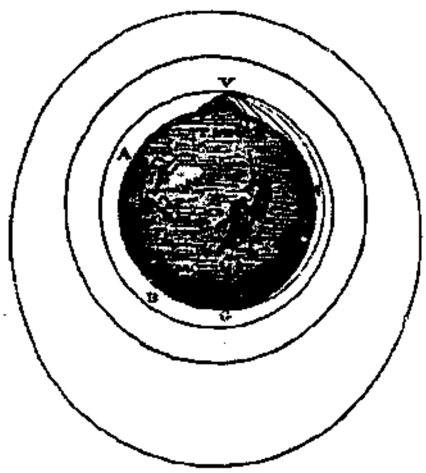
Scheme	Weight model
Scheme 0	There is only one weight concept (correct view).
Scheme 1	Weight (or weight force) is directly and unconditionally related to the empirical weighing results obtained by means of a calibrated spring scale.
Scheme 2	Observable or predictable alterations of weight are related to distance parameters, according to the rule "more distance less weight". This relation is not stipulated by any constraint.
Scheme 3	Observable or predictable alterations of weight are related to other forces or pressures (air, water or ground) which can compete with the gravitational force causing weight reduction or addition)
Scheme 4	Weight is due to the surrounding medium. This scheme extends scheme-3, claiming the *existence, creation, or transfer* of weight by the medium (air).
Scheme 5	Observable or predictable alterations of weight are related to the movement of the object (observer). Within this framework, sensations related to movement are interpreted as changes of weight.
Scheme 6	Weight is an inherent and invariant quantity of the body (like mass).

4.4.2.1 ORBITAL MOTION

Orbital motion is a form of falling that is confusing to many students as it involves understanding the interrelationship of concepts from rotational motion, (e.g., radial displacement, velocity, and acceleration), Newtonian mechanics and gravity in order to understand the basis of ongoing motion (e.g., Bar et al., 1997; Roschelle, 1991a, 1991b; Smith & Treagust, 1988; Treagust & Smith, 1989; Trumper, 2000; Vosniadou, 1989).

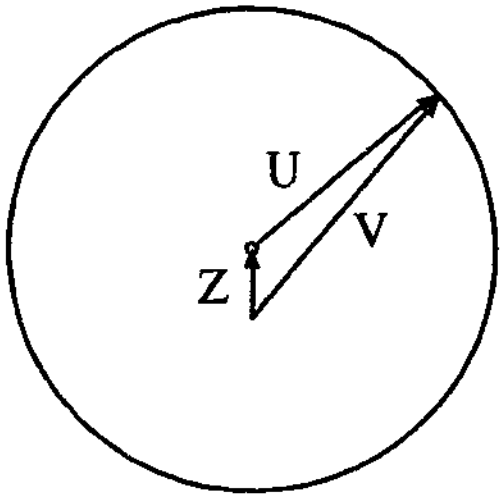
Links with two-dimensional projectile motion and orbital motion, while commonly depicted in textbooks (as in Figure 4-15), are arguably more complex for learners than they appear, requiring not only a re mapping of a horizontal plane to a sphere, but also requiring a change in coordinate systems from Cartesian to radial, and the concomitant comprehension of rotational dynamics quantities and units, with the associated reconceptualisation of Newtonian mechanics in a radial framework (cf. Barowy & Lochhead, 1980).

Figure 4-15: Classic illustration of the relationship between projectile motion and orbital motion (Holton et al., 1968, p.92).



In recognition of this cognitive complexity, Abelson, diSessa, and Rudolph (1974; diSessa, 1975) long ago recommended an alternative approach using velocity-space as a means of representation, rather than a three-dimensional Cartesian representation of physical space (Figure 4-16). In this model, the circle is generated by the traced out ends of the velocity vectors when the vectors are all drawn from a common reference point. The displacement (Z in Figure 4-16) of this reference point from the geometric centre of the circle is indicative of how closely the real orbit is to being circular. In this representation, U is the particular radius of the circle that points to the current velocity, V. While this model appears to have the advantage of simplicity of representation, it has not been widely used in educational research, with only a small number of studies employing the underlying concepts or similar visual elements (e.g., diSessa, 1982; diSessa & White, 1982; Roschelle, 1991b).

Figure 4-16: Velocity-space representation of an orbiting particle (diSessa, 1975, p.361).



In velocity-space, gravitational orbits are always circles (diSessa, 1975, p.360). This has the advantage of developing understandings of, for example, Newton's inverse-square law of gravity, from simple geometric propositions:

> A theory of orbits is developed for the inverse-square central force law which differs considerably from the usual deductive approach. This document begins with qualitative aspects of solutions, and leads to a number of geometrically realizable physical invariants of the orbits. Consequently, most of the theorems rely only on simple geometrical relationships.
>
> (Abelson et al., 1974, p.1)

Kass (1983) explored orbital motion and gravity concepts by having students predict the motion of an astronaut leaving a spaceship in Earth orbit. Nearly 50% of students predicted that motion would stop with the astronaut hovering over the Equator. Fewer students predicted that the astronaut would stay with the spaceship. Many students did not understand the gravitational nature of orbital motion, believing that the spaceship must use rockets to stay in orbit. Other erroneous ideas found include:

1. There is no gravity because the spaceman is weightless.
2. There is no gravity because there is no atmosphere.
3. Gravity acts on the spaceship, not on the spaceman (in space travel, it is the person who is described as weightless, not the spaceship).
4. Gravity is sometimes synonymous with an inertia-like "force forward". If gravity is absent the spaceman won't move forward.
5. The spaceman can hover in the Earth's gravitational field because the Moon doesn't get pulled to Earth (many different reasons were given for this).

Nelson (1991) examined explanations held by sixth grade students concerning gravity, orbit, and weightlessness, finding nine general explanatory categories for their beliefs (Table 4-3).

Table 4-3: Sixth-grade childrens' beliefs about gravity, orbit, and weightlessness (after Nelson, 1991)

CATEGORY	BELIEFS
Gravity	1. Gravity holds people and objects on the earth. 2. Air and the atmosphere influence gravity. 3. Gravity is a geocentric phenomenon.
Orbit	1. Orbiting objects move in space. 2. Force is required to maintain an object in orbit. 3. People and objects 'float' when in orbit.
Weightlessness	1. Weightlessness occurs in the absence of gravity. 2. Objects 'float up' as a result of weightlessness. 3. When weightless, people undergo physical and behavioural changes.

In examining the development of childrens' understandings of the dynamic nature of velocity and acceleration experienced by orbiting bodies, Roschelle (1991a; 1991b) found evidence supporting Forbus and Genters' Qualitative Process theory that suggests learning is sequential, with each stage being a prerequisite for the next.

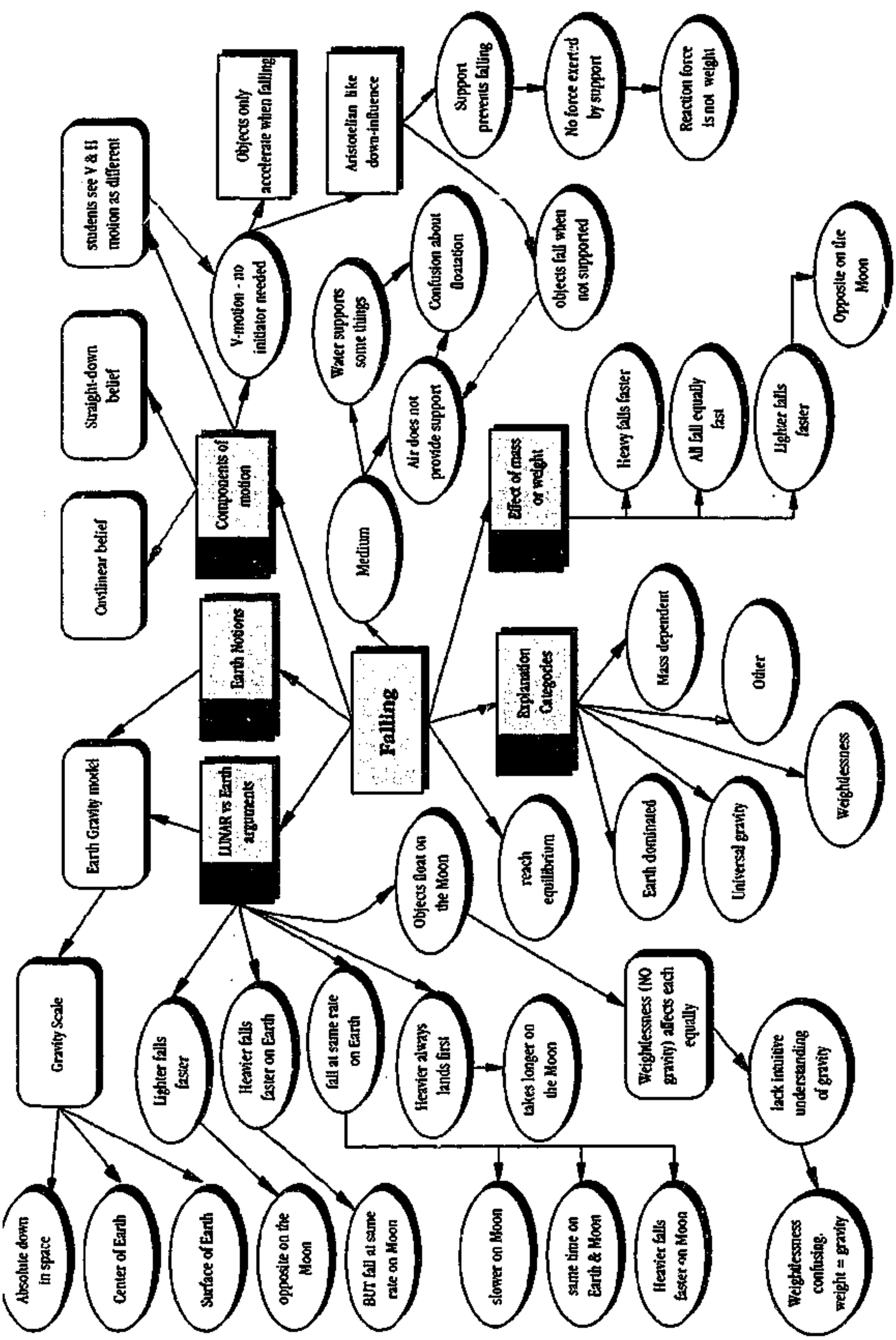
In this model, students development of qualitative knowledge passes through four stages:

1. Proto-histories (cf. diSessa's P-prims).
2. Causal corpus.
3. Qualitative models.
4. Quantitative models.

This may imply that in understanding orbital motion, there is a need for students to have at least developed through stages one and two in a number of different conceptual areas, and to be able to relate these together in stage 3. It is therefore reasonable and consistent with the research reviewed in this chapter, to expect that the responses of participants in this study to probes about orbital motion will include examples of their conceptual difficulties with underpinning concepts.

Figure 4-17 on page 129 depicts a range of student understandings of 'falling' in the context of both terrestrial and extra-terrestrial contexts. As discussed previously, this includes aspects of previous figures used in a different representation.

Figure 4-17: Students' beliefs about 'falling' (cf. Bliss, 1989; Galili, 1993, 1995, 1996; Nussbaum, 1979; Nussbaum & Novak, 1976; Nussbaum & Sharoni-Dagan, 1983; Sneider et al., 1986; Sneider et al., 1983; Sneider & Ohadi, 1998).



4.4.3 *Usage of the review findings*

The research findings described here were used, in conjunction with other sources such as the Force Concept Inventory (FCI) (Hestenes et al., 1992), to develop a framework for use in analysing the participants' responses to the probes used in the study. The framework was implemented as a structured NUD•IST index (Qualitative Solutions and Research, 1998, p.73-86) by exporting the structures of Figures 4-4 to 4-17 and then importing them into NUD•IST to make a prototype database which was subsequently fine-tuned manually. Responses other than those anticipated through the literature-based structured index were subsequently accommodated by the creation of 'free' nodes. For details of the index structure, see Section 5.8.1 on page 170.

4.5 Chapter Review

In this chapter, the subject matter knowledge base for teaching the gravitation unit of the VCE curriculum[29] was examined from the perspectives of historical models of mechanics, and misconceptions. These were reviewed in order to provide insight into the nature of the data that might be collected from the participants during the interview phase of this research.

29. Section A.1

Chapter 5

Methodological issues

"Anthropologists! Anthropologists!"

5

Methodological issues

> Yet the theories of science and the theories of practical activities are radically different in character because they perform quite different functions; they are constructed to do different jobs. In the case of empirical sciences, a theory is a body of statements that have been subjected to empirical tests and which express our understanding of certain types of events in the physical world. ... Where, however, a practical activity like education is concerned, the place of theory is totally different. It is not the end product of the pursuit, but is rather constructed to determine and guide the activity.
>
> (Hirst, 1971, p.342).

5.1 Introduction

In this chapter I discuss the methodological aspects of the study, describe the nature, use, and limitations of the instruments employed in the study, define their relationship to the research, and raise related issues. The structure of this chapter is informed by the three positions described below.

First, that the development of a research design is concerned with turning the research questions into projects (Robson, 1993, p.38; Sternberg, 1981, p.109), and that the strategies and methods that are used in carrying out research depend on the type of questions the researcher is trying to answer (cf. Hirst, 1971).

Second, in a position resonant with Driver's and Erickson's views on 'research programmes' in science education (Driver & Erickson, 1983, p.39; Erickson, 1999), that the paths that the researcher follows in developing an appropriate methodology are an important component of the research process itself

(Manstead & Semin, 1988). Accordingly, in this chapter, I have attempted to capture the processes that were followed in developing the final research methodology.

Third, I also adopt the methodological aspects of Cant's criteria (1996; 1997) for assessing quality in qualitative research: *justification* - that the work includes a justification of the selected methodologies (which follows); contextual-delineation — that there should be an acknowledgment of the relevance of the context in which the research takes place (as discussed in the introduction), which is similar to Leininger's 'meaning in context' (Leininger, 1994); *frame* — that the framework selected by the researcher to interpret what is observed should be discussed and articulated (which in this study is the external framework of Newtonian mechanics as discussed in previous chapters, and Shulman's PCK); and that the data sources should be evident and transparent to an external observer (as discussed below).

I begin this chapter with a discussion of general design issues (both theoretical and practical) that were considered in the initial development of this study, and how their resolution has shaped this work. This is followed by a justification of the chosen methodology and research methods. The research design and protocols are then discussed. The chapter concludes with an overview of the processes used in data analysis. The nature and use of the instruments employed in this study are provided in Chapter 6, and full details are provided in the appendices.

5.2 Aims of the research

The aim of this naturalistic and interpretive (as opposed to experimental) research study is to determine the nature of the participants' *T-PCK* and content knowledge of gravity in the selected VCE context, and to identify the nature of a knowledge-base (e.g., Bennett, 1993; Grossman et al., 1989) that could inform the development of software that could be constructed to support and facilitate the development of *both* T-PCK and content knowledge in this area of the VCE curriculum in a similar fashion to that in which *conceptual development* software is used to develop scientific content knowledge (e.g., CONDUIT, 1982; Knowledge Revolution, 1992; Murray, 1996; Windschitl & Winn, 2000; Wolfe, Edelson, Kass, & Davies, 2000).

The research does not seek to generalise beyond the original sample. A multiple case study design was employed, using a combination of quantitative and qualitative methods in order to collect rich, fine-grained data about the participants' knowledge and understandings of a number of gravitational contexts drawn from the VCE physics course.

In the longer term, it is anticipated that software derived from this knowledge-base will be useful in creating more meaningful learning experiences and teaching strategies to use in physics method classes — such as Andalaro's fuzzy logic microworlds (Andaloro & Bellomonte, 1998), Weller's diagnostic simulations (Weller, 1990), the CPU project at SDSU (Goldberg, 1997), the Maxwell World Virtual Reality Project (Dede et al., 1996), or in Brna's confrontation model (Brna, 1991), in order to help the participants become more effective, and more competent, physics teachers. Tsui et. al. (Tsui et al., 1994, 1995) have used a related similar[1] basis in developing an on-line, interactive database for the development of Hong Kong ESL teachers' content and pedagogical content knowledge, demonstrating the relevance of Shulman's model, and also the efficacy of collaborative, on-line environments in fostering the development of understanding at a variety of levels. A further long-term aim is to develop suitable pedagogical agents that can be used to scaffold the development of PCK in this area (e.g., Dowling, 2000; Passig, 2000).

The general notion of developing a 'knowledge base' *about* teachers' knowledge in order to develop systematic approaches to improving the quality of teaching is complementary to Bennett's notion of developing knowledge bases for learning to teach (Bennett, 1993). The former is external to the teacher, and develops from observations of teaching by an external observer — such as in a teacher-education practicum, and the latter is the individual teacher's development, grounded in classroom experience and professional activities. It provides a general structural model for the relationship between teacher educators and teacher education processes in a developmental frame, as opposed to contemporary competency-driven approaches.

5.3 Developing a focus

In the initial stages of this research, two fundamental decisions were made[2]. The first was to use a qualitative research framework. The second was to employ a largely computer-based approach to eliciting the participants' understandings.

1. In the area of ESL teaching, and not in terms of representation as per Magnusson, Krajcik, & Borko (1999).

2. The reasons for not using classroom observations are discussed in Section 5.5.1

These decisions were made on the basis of my preexisting involvement in the use of computers in Education (e.g., Braun, Collis, Moonen, & Nicholson, 1992, 1993; Nicholson, 1989, 1993a, 1993b, 1994a, 1994b, 1994c; Nicholson & Robinson, 1995), where I had developed a strong belief in the value of computational tools such as Logo and MicroWorlds for exploratory learning (e.g., Feurzeig & Lukas, 1972; Squires & Sellman, 1986), and from participation in a series of workshops by Andrea diSessa and Jeremey Roschelle on the use of the Boxer computational environment in science education research (diSessa, 1985b, 1985c; diSessa & Abelson, 1986). Visits to diSessa's research group at UC. Berkeley in 1991 and 1994, helped to confirm the research value of a computational approach to eliciting learners' understandings of physics concepts (e.g., Adams, 1988; Adams & DiSessa, 1991; Chait, 1993; diSessa et al., 1991; Leonard, 1991; Leonard, 1992; Minstrell & diSessa, 1994; Picciotto & Ploger, 1991; Ploger, 1988, 1991, 1992; Roschelle, 1991a; Roschelle, 1991b; Sherin et al., 1993).

A qualitative framework is implicit in this approach, and this also suited my purposes as I was not seeking to generalise from the findings; nor was the notion of statistical validity relevant here as there was no intention to collect quantitative data through an experimental design. It also matched my initial plans to use an action research approach to the study, but structural changes within the University, and particularly in the Faculty of Science and Technology, just prior to, and during, the period of this research meant that it was not possible, within the duration of this study, to actually be able to implement the findings in my physics method classes, and hence work through the action-research cycle (Kemmis & McTaggart, 1988a, 1988b; Watt & Watt, 1993) as was originally intended[3]. Instead, the thesis became an opportunity to use data collected from my preservice teachers to inform the development of a conceptual design for 'PCK-enhanced' software[4], the actual development of which would form the basis of a subsequent study, in a similar fashion to that in which diSessa's developing theoretical considerations of a 'principled design' for physics-software learning environments[5] both preceded and accompanied the development of Boxer from Logo (e.g., Abelson, 1984; diSessa, 1975, 1980, 1985c, 1986; diSessa & White, 1982; Sherin et al., 1993).

As a focus for the use of Boxer, I was strongly attracted to developing 'field turtles' — a class of Logo objects that can be used to explore interactions between objects moving in a field environment, as a way of exploring field concepts (Squires & Sellman, 1986). This seemed to be a potentially powerful way of exploring field concepts. An initial Boxer version was developed, but it was disappointing, suffering from Boxer's limited graphical capabilities. The serendipitous release of StarLogo, with its parallel-processing model, 'sensory' features, and powerful graphics capabilities appeared to provide an ideal environment to replace Boxer (Resnick, 1988; Resnick, 1993; Resnick, 1997).

At the outset, I had a general picture of the research to be undertaken, but I was not certain as to what was appropriate and achievable with the participants. In order to clarify my thoughts, and to examine StarLogo in detail, I visited some key researchers in relevant fields; Brian Harvey and Andrea diSessa at UC Berkeley (for

3. Structural and curriculum changes subsequent to the amalgamation between Deakin University and Victoria College led to the relocation and subsequent discontinuation of a physics stream in the Bachelor of Education.

4. The name, conceived for the purposes of this thesis, that I have given to the genre of educational software that this thesis seeks to describe.

5. focused on conceptual development and exploration of student learning.

their Boxer and computational expertise), Robert Lawler at Purdue (for a discussion about detailed case study approaches), and Mitchell Resnick at the MIT Media Laboratory (about StarLogo). The subsequent discussions helped to resolve a number of issues about the nature and direction of this research. Firstly, diSessa provided the perspective that a most important goal of contemporary science education research is to gather learner's 'stories' — to gather and reflect on their discourse and making of meaning, rather than their ability to perform specific tasks (A. A. diSessa: personal communication, 11/08/1994). This was not necessarily the kind of research that Boxer was originally developed to facilitate, but its successful use in ways which seemed to partly meet this goal was encouraging (e.g., Adams, 1988; Picciotto & Ploger, 1991; Ploger, 1991; Sherin et al., 1993). The discussion confirmed my view that a 'Boxer-like' approach was highly appropriate for probing my preservice teachers' understandings with computer-based tools (Nicholson & Vincent, 1994). Brian Harvey, however, cautioned that 'gravity' might be too simple a focus unless carefully defined by context — that students intuitively know a lot about it, even if they can not articulate it, and so research into their understandings should be based on carefully focused, specific instances (B. Harvey, personal communication, 11/08/1994). Robert Lawler provided compelling arguments for detailed case studies with one or more subjects. In particular the argument that the 'generalisable' case resulting from a conventional study, if it is in fact 'valid', must also include the particular case — the individual — and that such studies should be seen as complementary and not in opposition to larger group studies (R. W. Lawler: personal communication, 13/08/1994). In such cases, he recommended that the development of a rich corpus of detailed data should be a primary research aim in order to understand the detailed thinking of the individuals under study (cf. Tobin & Fraser, 1998, p.627). Resnick was able to confirm that StarLogo was a suitable environment to use in developing field probes, and that it would support the kinds of probes that I had initially envisaged. Additionally he indicated that the software might best be used in an exploratory way, with the users building microworlds rather than examining pre-built ones. He also suggested a tentative approach to modelling gravity in StarLogo (M. Resnick: personal communication 14/08/1994).

In the initial plan for this research, I adopted Resnick's suggestions, and planned to implement them in a series of Boxer-like, StarLogo microworlds in which the participants would develop computational representations of their physics knowledge. A pilot study was conducted to establish the feasibility of this approach, in which a prototypic StarLogo gravitational microworld was built by the researcher, and subsequently trialled with four preservice teachers. The development of the software confirmed StarLogo's potential in this research, with striking visual effects, and the ability to produce computer program code that modelled the concept being programmed. In the trial, the preservice teachers were asked to modify the software in order to describe other gravitational contexts. Unfortunately they quickly demonstrated that their lack of general programming knowledge and skills, let alone with the StarLogo dialect of Logo, was a fundamental impediment to this approach. This 'floundering' (Dorner, 1980; Goodyear & Tait, 1991, p.467) is a common problem in complex computer-based learning environments. In the Boxer studies, such as Adam's study of childrens' knowledge of dinosaurs (Adams, 1988) or Ploger's work with understanding molecular structures in biology (Ploger, 1988, 1991; Ploger & Harvey, 1988), a significant amount of the research time was spent facilitating student learning about Boxer, either formally from a researcher, or informally as part of the research (S. Adams, personal communication, July 1991). In this study, I was not permitted, as part of Deakin's consent to the research study, to make 'excessive' demands on the participants' time, nor were the participants prepared to make themselves available for prolonged involvement in this study.

For these reasons, and much to my disappointment, my original intentions had to be modified to accommodate the participants' situation, and to ensure their ongoing participation. Subsequently, development proceeded along the line of developing more traditional forms of probes, such as 'predict-observe-explain' scenarios (Bliss, 1989; Gunstone & Watts, 1985), and the development of 'discrepant events' in mechanics and gravitational contexts (Fensham & Kass, 1988). These were to be used in a clinical 'interview about circumstances' (Gilbert & Osborne, 1980, p. 666; Osborne & Gilbert, 1980) in which the participants would be required to respond to the various probes.

5.3.1 The research genre

In this section, I discuss the key methodological perspectives that informed the research design, and argue for the validity of both the chosen methodology, and the use of the variety of data collection methods that were employed in this study.

'Conventional' and 'applied' research can be differentiated by their characteristics (e.g., Jacob, 1989). Conventional research is commonly positivistic and theory-informed — driven by theoretical perspectives and issues, and contains structural features designed to minimise external influences and effects in order to maximise the 'objectivity' and generalisability of the findings (Adair, Sharpe, & Huynh, 1989; Bracht & Glass, 1968; Cook, 1962, 1967; Rowell, Dawson, & Madsen, 1993, p62). Such research is frequently quantitative and experimental, with a focus on statistically valid results (cf. Campbell & Stanley, 1966, p.1). In regard to this research paradigm in the context of science education research, White notes that ...

> Reasons why learners differed in abilities, attitudes or knowledge were not considered, and nor were the mechanisms whereby these differences came to affect learning - it was sufficient that they did. (White, 1988, p.16)

The links between experimental research and behaviourist psychology are evident here. For similar reasons to those that saw behaviourism replaced as the dominant psychological paradigm during the 1960's, educational researchers also began to adopt and adapt non-behaviourist, qualitative research paradigms that provided more insight into their subjects' thinking, problem solving processes, and skills (Denzin & Lincoln, 1994, p.ix; Jacob, 1988, p. 16; 1989). White also comments that:

> Indeed it is only by considering the achievements and failures of that style of research that scholars have come to treat learning as a more complex phenomenon, and have come to carry out more subtle and sensitive investigations... (White, 1988, p. 17)

An alternative perspective on educational research paradigms is based on purpose rather than process, in which the two foci are to '...explain and to establish causal relationships, or to understand and interpret.' (Husén, 1988; Keeves, 1998, p.1133; Lincoln & Guba, 1985). This is not the same distinction as between qualitative and quantitative paradigms (Keeves, 1998, p.1134; Keeves & Alagumali, 1998, p.1229-30).

5.3.2 Research traditions

Applied research does not have a primary concern on quantitative, generalisable results, and statistical validity. It embraces wider viewpoints on the issue of what constitutes 'research', and has a less rigid conceptual framework in which qualitative and interpretive research are both valued and legitimised (e.g. Jacob, 1987; Phillips, 1987). As such it embraces methodologies and methods such as ethnography, phenomenology, hermeneutics, case-studies and action research (diSessa, 1983; Fitzgerald, 1997; Husserl, 1970; Kemmis & McTaggart, 1988a; Lincoln & Guba, 1985, p.59-61; Luckmann, 1978). These different practitioner 'traditions' (Jacob, 1987, 1988) reflect a wide range of different epistemological views of both knowledge and the 'orthodoxy' of particular research paradigms. Buchmann and Floden (1989, p. 243) however raise the issue of the weakness of the actual notion of 'traditions' in social research, questioning its relationship to Kuhn's conceptualisation of a paradigm (Kuhn, 1962; Mastermann, 1970), and the relatively short term during which any semblance of a real 'tradition' has had time to emerge in western social and educational research.

The adoption of a qualitative research model provides the researcher with many options for choosing an appropriate methodological stance, and, as such, allows for the possibility of the partial adoption of elements from any or all, as in this study — a situation that has, at times, raised concerns in the research community. Jacob

(1987), for example, expressed concern about the eclectic use of methodologies and methods drawn from across a range of traditions, arguing instead for an orthodoxy of qualitative research traditions similar to that embedded in the positivistic, experimental paradigm of conventional research:

> ...educational researchers who do not adhere to a package of assumptions, foci and methods will take a piece here, and another there, leading to studies that are "likely to be poorly focused, conceptually unclear, and weakly implemented" (Jacob, 1987, p.40)

Leininger (1994) essentially supports this viewpoint from an epistemological perspective, arguing that:

> ...one cannot mix research methods across qualitative an quantitative paradigms, but one can mix methods within each paradigm. Mixing methods, goals, and purposes across the paradigms violates the intent and philosophical purposes for each paradigm. (Leininger, 1994, p.101)

These conservative viewpoints have been disputed on several grounds. From an historical viewpoint, Goodwin and Goodwin comment that:

> Historically, those who believe that the differences between qualitative and quantitative research approaches are primarily technical ... have advocated 'mixing and matching' methods to fit the needs of the research question. (Goodwin & Goodwin, 1984, p.378)

At a pragmatic level, Atkinson et. al. argue that:

> Much sound work explicitly or implicitly combines emphases from different traditions, without seeking to establish a new 'tradition'. (Atkinson, Delamont, & Hammersley, 1988, p.233)

At a functional level, Lawler (1996, p.2), argues against, 'letting a rule-laden methodological "tail" wag the research approach "dog".' Lawler argues for a more pragmatic and robust research approach, claiming that convention has overtaken intent as procedural rigour has 'overshadowed the key elements of approaches.'

> The inherent danger is that researchers new to qualitative approaches ... tend to treat the mechanistic steps outlined in ("how to") texts as rules which must be followed. (Lawler, 1996, p.3)

In the context of science education, Keeves (1998, p.1133), argues strongly that there is no one method of science education research, and that the methods that are employed '...are not only dependent on the nature of the problem, but also on the knowledge, understandings and skills that the researcher brings to the task'. Pragmatic research designs are also strongly supported by Hakim, who moves beyond Lawler's procedural concerns to include the adoption of idiosyncratic elements that accommodate the individual researcher's 'personal style'...

> It is also very much about style, the architect's own preferences and ideas (whether innovative or solidly traditional) and the stylistic preferences of those who pay for the work and have to live with the finished result. (Hakim, 1987, p.1)

Erickson (1999) also argues that the past thirty years of science education research has shown very clearly that there is a strong case to be made for science education research to be much more practical and pragmatic in its focus and methodologies.

Aspects of these positions can be found, to varying degrees, in practice. For example, the formal distinction between conventional and applied research traditions is not always clearly observed in practice. Rowell (1993, p.62) comments that while much of the published science education research is essentially applied research, in fact it contains many of the characteristics of conventional research as it attempts to be as relevant to as large an audience as possible. For example, Selman's study of 'unseen force' in children's theories of electromagnetism and gravity assumed the existence of a Piagetian developmental framework (to be added to by the research), included processes of 'validation' and statistical analysis, and explicitly discussed the generalisability of the findings (Selman et al., 1982, p. 182-4). Similarly, Nussbaum's (1976) study of children's concepts of the Earth led to the development of a hypothetical, hierarchical, developmental framework which was subsequently posited as generalisable, and which later formed the subject of further research (Nussbaum & Sharoni-Dagan, 1983) and external verification of both the conclusions and methodology (Sneider et al., 1983). At the same time, these studies also provided meaningful data about the children's thinking about the relevant scientific concepts, showing to varying degrees the value of using more focused and inclusive methods than those dictated by rigid adherence to methodological orthodoxy.

In this study I have adopted the essential positions of Atkinson, Erickson, Hakim and Lawler — that the research design does not need to be constrained by a presumed methodological orthodoxy or tradition — in developing an approach to this research that incorporates a range of methods of data collection, and which employs a variety of media and representational forms. The latter was a reflection of both the researchers' personal style and preference (cf. Hakim, 1987, p. 1).

5.3.3 Case study research

The 'case study' methodology (Neumann, 1989) is a class of qualitative research that has the following characteristics (Robson, 1993, p. 52):

- A strategy, i.e. a stance or approach, rather than a method, such as observation or interview.
- Concerned with research, taken in a broad sense.
- Empirical in the sense of relying on the collection of evidence about what is going on.
- About the particular; a study of a specific case.
- Focused on a phenomenon in context.
- Using multiple methods of evidence or data collection.

Stenhouse (1985) has identified four types of case studies — ethnographic, critical action, evaluative, and educational. In the main, these are methodological genres of case study research that are applicable to researching systemic educational problems (e.g. Lightfoot, 1963). His 'types' relate to understanding social forces, organisational culture, systems or group behaviour, rather than individuals, and as such do not include the types of micro-scale case-study research that this thesis is concerned with. Robson (1993) uses a different classification scheme to describe five types of case study as listed below in Table 5-1 below.

Table 5-1: Robson's case study classes. (Robson, 1993, p.147)

Class	Attributes
Individual case study.	Detailed account of one person — examines contextual, antecedents, perceptions or attitudes.
Set of individual case studies.	As above, but a small number of individuals with some features in common.
Community studies.	Studies of one or more local communities.
Social group studies.	Studies of both small, direct contact groups and larger more diffuse groups.
Studies of organizations and institutions.	Studies of firms, work-places, schools and similar organizations.
Studies of events and relationships.	Focus on a specific event (overlaps with the last two categories above).

In accordance with the discussion in the previous section, and adopting Robson's sixth point above, the stance that is employed in the present study draws its roots from a variety of sources — particularly the genres of detailed micro-scale case studies (e.g. 1979; Lawler, 1985; McDougall, 1988), the use of Boxer and computer microworlds in probing cognition (e.g., Chen, Lieberman, & Paisley, 1985; diSessa, 1980, 1988, 1989; diSessa et al., 1991; Hennessy et al., 1990; Ploger, 1992), 'interviews-about-circumstances' (Bar et al., 1997; Bar et al., 1994; Gilbert & Osborne, 1980; Nussbaum & Novak, 1976; Piburn, 1988; Swan, 1997) as a means of eliciting understanding, 'predict-observe-explain' situations (Bliss, 1989, p.266), and 'discrepant events' (Fensham & Kass, 1988).

The attributes of the case study approach as outlined above are well matched to the needs of this study; a focus on the particular — each of the participants, focused on a phenomenon in context — their understandings of the Newtonian force concept in the context of planetary gravitational fields, and aimed at getting evidence about 'what was going on' in terms of their thinking, and seeking elements of their PCK. The axiomatic acceptance of multiple forms of evidence in this methodology also suited my personal desire to use a variety of approaches (as per Hakim) in order to explore both the effects of various representational forms on the participants' thinking, and to provide richer stimuli than those commonly found in text instruments in order to gather rich data about their understandings.

Common critiques of case study approaches to research are that they are anecdotal, non-scientific, not objective, and cannot be generalised from (Walker, Lewis, & Laskey, 1996, p. 41-42). As discussed previously, these are common complaints across a wide range of qualitative methodologies, and can be viewed as arising from the alternative epistemological perspective of quantitative methodologies. Walker et. al., however, consider that the lack of generalisability is a key feature of the case study approach:

> Case studies that are more than superficial have the capacity to stall any attempts that are made to generalise or theorise from a narrow conceptual base. Case studies are best used to counter generalisations, not exemplify or support them. (Walker et al., 1996, p. 41)

In regard to detailed micro-scale case study research, Lawler points out that the general case must include 'the particular case', and that studying the particular case by means of detailed case studies provides a richer view of the complexities of the general case, a position in agreement with Walker's view. This position in regard to the individual case is central to this thesis, as I focus principally on determining individual participants' understandings, not of the group as a whole.

The methodological framework that I have adopted for this thesis is a 'multiple case study' design (Robson, 1993, p.161) implemented as a series of semi-structured interviews (Arons, 1990, p.v) involving the use of both written and computer-based items (cf. Ganiel & Idar, 1985; Gorsky & Finegold, 1992; Hennessy et al., 1993). This approach is informed principally by Lawler's model of developing a corpus of detailed, fine-grained data about the individual subjects in accordance with the views expressed above (Lawler, 1979, 1985; Lawler & Carley, 1996; Walker et al., 1996, p. 41).

5.4 Granularity – the need for fine-grained data

One of the major concerns I had in this study was to ensure that the probes provided 'fine-grained' data about the extremely narrow range of contexts that form the focus of this research. In planning the research for this study, it was clear that the narrow range of concepts being probed needed to be examined in-depth across a range of contexts related to the way in which the material is taught in the classroom, rather than by a coarse-grained evaluation that may not have proved capable of producing adequate data. Tobin and Fraser (1998) provide a strong theoretical justification for using a qualitative approach to eliciting fine-grained data in contexts similar to that of this thesis, and effectively restate Lawler's belief that the development of a rich corpus of data is an essential aspect of any cognitive study (as above):

> Different research studies call for a focus on different levels or 'grain sizes' which, in turn, have implications for the choice of research methods. For example, a fine grain size involving a contrast between two teachers or between several students within a class (e.g., Tobin, Kahle, & Fraser, 1990) normally requires intensive qualitative interpretive methods. (Tobin & Fraser, 1998, p.627)

Working with adults who presumably have had more experience with, and better knowledge of the subject matter, suggested that it would be possible to get quite detailed information about their understandings of the VCE content. This is in contrast to many studies conducted with school children where quite 'coarse-grained' data are routinely collected through the use of relatively small questionnaires and interviews. Vosniadou (1992) for example studied the development of conceptual knowledge about the earth among 60 elementary school students through a short questionnaire about the Earth's shape. Gunstone's (1987) large scale survey employed a number of probes to examine university students' knowledge of gravity. A large amount of data were collected across a range of contexts, but with little depth in terms of the cognitive aspects of each of the items — the survey produced a broad profile of the students' understandings across a range of tasks, but did not examine the detailed cognitive issues underpinning them. Ameh's (1987a) study of Nigerian science teachers was based on a relatively short and broad survey instrument, that again provided an overview but did not address the teachers' detailed thinking about the cases presented to them in the survey (R.F Gunstone – personal communication, July 1997). White's (1990) study of young childrens' mental models of gravity and their interpretations and explanations of the free fall of objects used a short, Predict-Observe-Explain (POE) instrument to probe their understandings. Similarly, both the widely used Force Concept Inventory (Hestenes et al., 1992) and Mechanics Baseline Test (1992) are effective at diagnosing the presence or absence of specific Newtonian concepts, but provide no data whatsoever about the students' understandings of those issues.

The value of research methods (and findings) such as those discussed above are not being criticised here; but are raised as examples of how the commonly used methods of physics education research do not necessarily provide the type of data that was sought in this study. In contrast, the detailed findings of many micro-scale cognitive case studies that sought more detail about a small range of cognitive issues appeared to produce the type of data that seemed to be needed in this study. Roschelle's 'Envisioning Machine' for example provided an environment that allowed the development of highly detailed qualitative case stories which documented the subjects' development of understanding of velocity and acceleration in trajectories (Roschelle, 1991b). In common with many of the Boxer studies of science and mathematics understanding (e.g. Adams, 1988; diSessa, 1989; diSessa & White, 1982; Minstrell & diSessa, 1994; Picciotto & Ploger, 1991; Ploger, 1991, 1992), such studies can provide detailed understandings of very specific items, or significant details of developmental processes.

The argument above is not one for Boxer, but for the way that Boxer (like Starlogo) has routinely been employed in science education research — gathering detailed, incremental, (usually) individual, micro-scale data about physics concepts or contexts. Boxer's computational model greatly facilitates this process by forcing the development of explicit representations[6] that may not have been forthcoming in other approaches. Using Boxer or StarLogo in this way was my preferred method of data collection, but as discussed previously, this was not possible. Any replacement had to be able to generate data of a similar level of detail, but not necessarily in a computational format.

6. i.e., the program code, structure, and visual representations.

The use of rich visual media such as contextual cartoons, computer-based probes and computer simulations was an attempt to provide rich visual environments for the participants' that contained a lot of features to talk about. Bliss (1989) employed cartoons to avoid tasks which might suggest "scientific" responses, attempting to find '...ordinary natural situations that would elicit common-sense answers' (p.267), and in which

> ... it is important ... to find a 'normal' world (simulation or model) in which the REAL 'normal' world rules could be suspended....so that it seemed reasonable to ask if such rules DID apply. (Hayes, 1979, p.267)

In this thesis, cartoons act as 'normal' (cartoon) worlds in which the real laws of physics have been suspended, and so allow the question above to be put to the participants' of this study.

The value of static cartoon pictures in constructivist science teaching has been demonstrated (e.g., Keogh & Naylor, 1997), and the importance of context emphasised by Black (1993). Keogh et. al. (1997, p.134-5) demonstrated that cartoons were an effective way of eliciting learners' ideas, '...with numerous teachers commenting on how the cartoons "were particularly revealing of the pupils' conceptual development"', and also of helping learners to merge, 'the elicitation and conceptual restructuring stages of the constructivist teaching sequence'. The use of contextual video cartoon sequences therefore seemed likely to be able to produce similar outcomes, and perhaps produce even richer data because of their dynamic representations of events. Keogh et. al. (1997) also tentatively suggested that cartoons were an accessible entry into physics for some females. This suggestion of 'female friendliness' was a further consideration in the adoption of cartoons in this thesis.

In an attempt to generate fine-grained data — to capture subtleties in participants' understandings or explanations, some of the situations consisted of sets of graded scenarios, in which each item was followed by a slightly more complicated one, or one which extended the same situation into a different context. It was hoped that this would lead to a progressive revelation of understandings by the subjects in a way similar to that in which each iteration of Boxer code captures the embedded understandings of the programmer. A research design that attempts to generate such fine-grained data is embedded in the items listed in Table 5-2 below (continued on the following page).

Table 5-2: Research design for capturing fine-grained data

Item	Components	Features	Granularity
Field dependence-independence probes	Two sets of graded probes examine the subject's ability to identify motion from the visual clues in the probes.	1.5 stages from 1D linear motion to 3D curvilinear motion 2. 3 stages from uniform field to radial field.	Provides eight sets of responses about the ability to identify and describe simple particle motion in spatial situations.
Cartoon probes	Five video clips which contain multiple instances of relevant physical situations in the context of cartoons.	Repeated instances of similar events in different contexts for cross checking and verification of consistency of responses and of conceptual understandings.	Extensive verbal responses about similar and different examples that in total provides a rich corpus of data about projectile motion, gravity and free fall.
Field probes	A set of ten computer microworlds consisting of planetary systems of increasing complexity and/or alternate format.	Repeated instances of radial gravitational fields and point-to-point interactions, graded from single to multiple-body cases.	Extensive verbal responses about similar and different examples that in total provides a rich, detailed corpus of data about planetary gravity, gravitational field and orbital motion.

Vector probes	A set of 5 computer microworlds that provide explicit vector and graphical representations of the events depicted in a graded set of probes.	Quantitative representations of scenarios previously examined qualitatively.	Cross-referencing, and verification of, subjects' explanations through reviewing key ideas from a quantitative framework.
Force Concept Inventory	A multiple choice instrument for probing participants' understandings of the Newtonian force concept.	Situations in which the subject has to choose between a correct Newtonian response and common sense alternatives.	Data set with five components — profile of the participants' understandings of the Newtonian force concept in five conceptual categories.

5.5 The clinical interview

A clinical interview (Pines, Novak, Posner, & Van Kirk, 1978) was used to collect qualitative data. This method is one of the most common methods employed in science education research into alternative conceptions (Wandersee et al., 1994, p.200). It was designed as a semi-structured 'interview about circumstances' (Gilbert, Watts, & Osborne, 1985; Piburn, 1988), or in Powney's schema, as a non-directive informant interview model (Powney & Watts, 1987, Ch.2). This was designed to elicit fine-grained data about the participants' knowledge of a series of gravitational contexts. This formed the core of the research method employed in this study. The data generated by the interview complements that gained from the Force Concept Inventory which, 'must be supplemented by information from other sources to get a reliable profile of student understanding' (Halloun & Hestenes, 1995, p.2).

The rationale for using a clinical interview for probing thinking and understanding is essentially the same one as Piaget gave for his clinical method — it is highly flexible, allowing a skilled researcher to direct or adapt to the flow of conversation

(Posner & Gertzog, 1982, p197). This allows the researcher to probe areas of knowledge by letting the subject speak freely, as the researcher concurrently checks the responses to identify ones of interest or significance to follow up on with a subsequent question. It therefore provides the opportunity to explore responses and issues that could easily be overlooked in a formal structured interview employing a predetermined set of questions to be followed linearly (Brenner, 1985, p.11). Such an approach was considered to be essential in this study where the use of cartoons and computer microworlds was likely to result in a wide variety of unanticipated responses that required follow up questions.

5.5.1 Issues in physics education research

Niedderer et.al. (1992, p.11) question how the characteristics of educational research performed in a clinical setting, as in this study, differ from those performed in the classroom in terms of the information gathered about thinking and learning. Lemke (1998, p.1185) raises similar concerns in regard to the differences in the nature of the discourse between the two contexts. This was a concern — whether or not the study should have been based around classroom observation rather than an interview model. I decided to use a clinical approach for two reasons. First, my informal observations of the participants teaching in the classroom suggested that it would most likely require an extensive period of observation in each classroom to gather substantial data on their teaching. I observed that most lessons consisted of brief explanations (which were the focus of the study) of some 10 – 15 minutes, followed by extended periods in which the pupils worked on problems or practical activities. Second, as only three weeks per year were devoted to the teaching of this topic, it was unlikely that I would be able to observe each and all of the participants in that time for a sufficient number of hours to be able to gather meaningful data. This was compounded by the geographic spread of the schools the participants were placed in, and the concurrent nature of their practicum program meant that they were all undertaking their teaching practicum simultaneously, and that this was unlikely to coincide with the desired physics topic being taught.

A particular consideration in this study was the desire to have the participants' respond to questions arising from the probes in a similar way to that in which they were observed to do in classrooms[7], in order to attempt to both elicit elements of PCK such as might actually be used in responding to students in classrooms, rather than to the interviewer in a specific interview/conceptual context[8]. This issue raised a significant methodological issue about the conduct of the interviews. In many semi-structured interviews that probe for conceptual understandings alone, responses to questions are commonly explored in a detailed, iterative, and threaded manner in order to tease out their conceptual origins. Such an approach requires detailed questioning from the interviewer about key issues (from the interviewers perspective) raised in each response (iteratively). A perceived problem with such an approach, for the purposes of this thesis, was the potential to drift away from a focus on pedagogical aspects through focusing too heavily on the conceptual aspects (whilst noting their interrelationship in Shulman's model).

A pragmatic decision was made to attempt to minimise such potential drift by

7. cf. Lemke (1998) p.1185

8. as opposed to a classroom context or situation.

responding to participants' responses with further questions which attempted to elicit the meaning of their responses, rather than to tease out the conceptual underpinnings — as perceived by the interviewer (cf. Oakley, 1981, p.37; Selltiz, Jahoda, Deutsch, & Cook, 1965, p.576). It was felt that this decision, whilst potentially reducing the extent of exploration of conceptual issues, was in accordance with Erickson's (1999) call for more pragmatic research designs by attempting to adapt a proven approach to probing conceptual understandings, to capturing elements of PCK.

The clinical interview provided an intense, more focused, and more likely source of rich data in a manageable and realistic time scale that would enable all of the subjects to be interviewed in depth. The use of computer probes and video in the interview process also enabled detailed recordings of their thoughts, actions, and explanations to a level of detail that would probably have been difficult to elicit through classroom observation.

5.5.2 Gender Issues

The participants of this study consisted of approximately equal numbers of males and females. This was a higher proportion of males than in the actual classes, which over the three years averaged approximately 40% males and 60% females. The higher percentage of females enrolled in what has traditionally been seen as a male subject (especially in secondary schools) (e.g. Di Pilla, 1996; Dunbar, 1990; Hildebrand, 1996a) is explained by the diversity of courses that can be combined with physics in the Bachelor of Education course. Over the period of the study, a significant number of female students came from drama, English and physical education courses — which historically at Deakin (Rusden campus) have had high female enrolments. These acted as enabling pathways for females who wished to continue their secondary school interests in science into their teaching career.

Although I had successfully taught these classes for a number of years, and personally considered that I had developed a pedagogical approach that was sensitive to females' perceived learning styles, I was conscious of some of the agendas of feminist science education research such as positionality (e.g. Barton, 1998, p.119-123) and its impact on the feminist view of 'gendered' research methods (e.g. Davidson, 1994; Harding, 1989, 1991; Kahle & Meece, 1994; Roberts, 1981). I was specifically concerned about a feminist perspective on interview-based research — that the differential relationship between the researcher and respondent has the potential to 'exploit' participants (cf. Harding, 1989; Oakley, 1981, p.31-40), especially when the researcher is male and the participant female[9]. It seemed likely that similar concerns could be applied to the *semi-structured* interview used in this study, although in this case the respondent is more empowered by the interactive and responsive nature of this interview format. In order to minimise any such influence, sense of coercion, or unease in the interview process, I employed three strategies for all of my participants, both male and female.

First, I carefully explained (as required) that the University Ethics committee approval of the research was conditional on informed consent, and the ability of the subject to withdraw at any time, without penalty of any kind. Second, I elaborated

9. this can also occur in same-sex contexts; see Oakley (1981) p.46-51 for similar issues relating to feminists interviewing women.

on this by pointing out that the research was not in any way connected to their academic studies or my assessment of their work. To ensure that this was so, I arranged to conduct the interviews after my assessment of their performance in physics method studies was completed and formally submitted to the University. Third, in terms of the actual conduct of the interview, I explained that the need to conduct it in a closed room was due to the need to make a clear recording of the dialogue, and if they felt uncomfortable about that, that they were welcome to invite a third party of their choice to join them for the interview. Additionally, sufficient space was provided around the computer and television for them to decide on their proximity to the equipment and to the researcher.

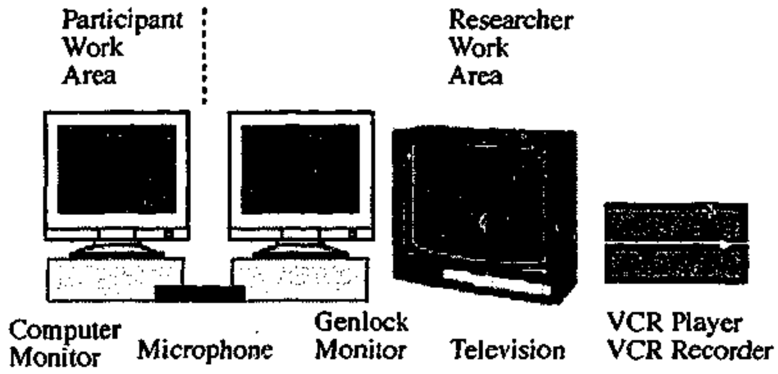
5.5.3 The intrusion of technology

Traditionally, interviews are conducted under circumstances that try to put the subject at rest, in order to facilitate free and open discussion about the issues being examined. I was concerned that the participants may have been distracted or bothered by the equipment used in the interview process, and that this would affect their responsiveness and attention to the interview tasks.

In this study I employed a tape recorder to record the interview, and a video recorder to record the on-screen actions of the participants. The video recorder also recorded the voices throughout the interview (as a backup for the tape recorder). Both for practical reasons, and in accordance with Thompson's notion of research 'honesty' (Thompson, 1996, p.5), the tape recorder and microphone were placed on the desk next to the computer monitor. The interviews were conducted in a small office

(2.1m x 3.3m) crowded with the technical devices employed in showing the video-clips, recording the dialogue, and capturing the subjects' interactions with the computer probes on the screen. The equipment consisted of a computer, two computer monitors, a 60 cm television set, two video cassette recorders, a tape recorder, video gen-lock[10], and a camera arrayed around, and in close proximity to, the participants as in Figure 5-1.

Figure 5-1: Layout of the research area for phase two.



In this environment, it is legitimate to consider if the technology became a mediating or inhibiting factor in the research process. Ellul (1962) and Thompson (1996) have challenged notions of the perceived neutrality of technology, and each argues that it can impact on the research process. Drawing on Idhe's (1979; 1982; 1990) notions of the transformative influence of media on communication (cf. Givens & McShea, 2000, p.129), Thompson further argues (1996, p.4) that the technology can have a mediating effect, either positive or negative, on the discourse and its subsequent analysis, and that subsequent analysis can allow, '...greater analysis of the subtleties of speech than in normal conversation'. (p.7) Thompson

10. An electronic device to facilitate the video recording of computer monitor signals.

perceives this as creating a tension between the function of the technology in recording data, and in its subsequent role in analysis and manipulation of that data.

In accordance with the general cautions of Metzler (1977), Gorden (1975) and Thompson (1996, p.3), I endeavoured to minimise the physical presence of the technology by locating as much of it as possible in one place alongside the desk, away from the participants, so that they faced onto a computer and tape recorder. I also placed their side of the desk near a window that afforded a view across the campus. This provided the participants with a relatively normal office-desk environment. Most of the equipment was not visible when they were engaged in tasks on the desktop, except when they had to turn to watch the television, when they were confronted by the entire assemblage.

In conducting the interviews, I adopted the same conversational approach that I had employed with them previously over the semester when they had come seeking help with their physics education tasks. In this way, I hoped to minimise any effect that the presence of the technology or the uniqueness of the situation might have had on them.

5.6 The Research Protocol

This section describes the structure of the research protocol used to elicit content and PCK data in the student-teacher interviews, and the nature and use of the various components that were employed in them. Their rationale and design is discussed and related to the VCE context, and relevant research.

5.6.1 Overview

The research protocol for the interview phase consisted of two stages that were conducted in two separate sessions as depicted in Figure 5-2 and Figure 5-3.

Figure 5-2: Stage 1 of the research program - focus on conceptual knowledge.

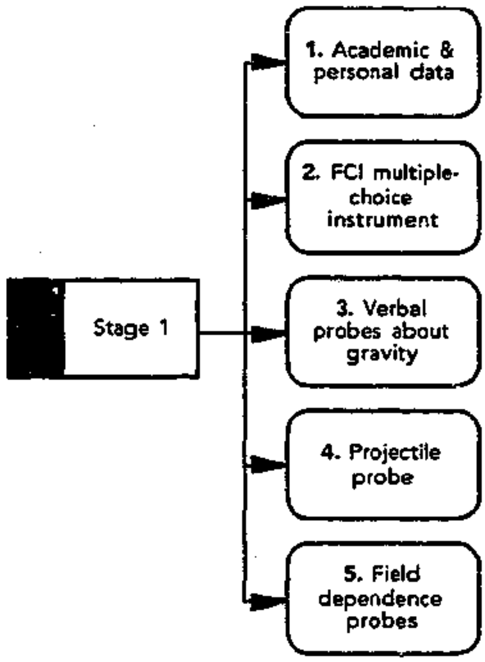
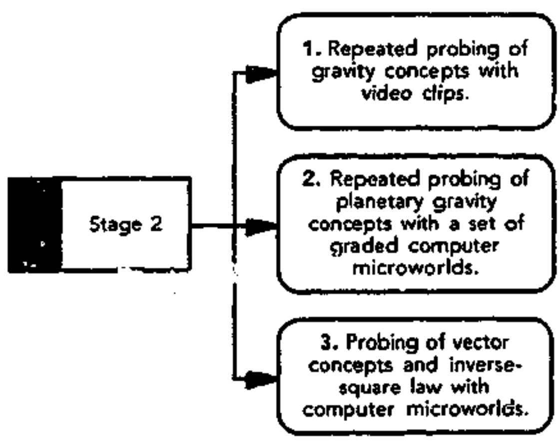


Figure 5-3: Stage 2 of the research program - focus on representation.



The total time commitment for the participants was a minimum of 1.5 hours depending on how long they took to complete stage two. The average time taken to complete the two stages was approximately two hours, consisting of 40 minutes for stage one, and the remainder for stage two. The content of this two-stage interview was drawn from the VCE physics curriculum module 4.

Stage one involved the collection of basic personal and academic data, the completion of the Force-Concept Inventory (FCI) multiple-choice instrument, 'projectile' probe, and the two field-dependence probes. The focus in this stage was on the subjects' content knowledge — their understandings of the Newtonian force concept, and to test them for field dependence-independence, as this *may* affect the way in which physics learners perceive and process information (e.g., Myers, 1997). In a significant number of cases, participants' time constraints dictated that the field-dependence probes were conducted in a separate subsequent session.

Many studies have shown that learners have difficulties with the physics concepts relevant to projectile motion (e.g. McCloskey et al., 1980; McCloskey & Kohl, 1982; McCloskey, Kohl, & Washburn, 1981). A 'projectile' probe was used to collect baseline data about the participants' understandings of two-dimensional projectile motion. Combined with the FCI results, this data was important for determining their understandings of projectile motion because, in this study, projectile motion is effectively extended to include motion in radial, planetary gravitational fields. It was hoped that this baseline data would be useful in identifying common or additional conceptual difficulties that arise in explaining motion in these more complex contexts. Table 5-3 below lists the components of the first stage of the interview protocol.

Table 5-3: Stage 1 of the research protocol

Stage 1 Components (Focus on conceptual understanding)
1.1 Collection of course details, academic background, personal data and contact details.
1.2 Multiple choice instrument completed.
1.3 Initial verbal probes on: • definitions; • examples of 'gravity'; • detecting its presence or absence.
1.4 Projectile probe: • Examine common conceptual problems. • Verify and expand responses in multiple choice instrument.
1.5 Field dependence probes • Probe for field dependence-independence

Stage two focused on attempting to collect data that were suitable for examining both the subjects' PCK, and their content knowledge of gravity. The strategy employed was to use cartoon video clips (cf. Bliss, 1989; Park & Lamb, 1992) and computer microworlds (Andaloro et al., 1997; Bliss & Ogborn, 1989; Brna, 1989, 1991; Champagne, 1980; diSessa, 1975, 1980; diSessa & White, 1982; Hennessy et al., 1990; Lawler, 1984; Nicholson, 1994c; Osborne, 1987) as a focus for developing an ongoing discourse about the nature and effect of gravity on a variety of moving and stationary objects in terrestrial and planetary contexts. These were similar to, or extensions of, situations that they would confront in their VCE physics teaching. Table 5-4 below lists the components of the second stage of the interview protocol.

Table 5-4: Stage 2 of the research

Stage 2 Components *Focus on pedagogical understanding*
2.1 Repeated probing of gravity concepts related to projectile motion, gravity, inertia and force through the use of five cartoon video clips.
2.2 Repeated probing of planetary gravity concepts, Kepler's laws, field concepts, and Newtonian concepts through the use of ten graded computer microworlds. Includes part two of field dependence probes.
2.3 Probing of vector concepts and the inverse square law through the use of five computer microworlds.

While the data from stage two was anticipated to raise pedagogical issues in accordance with Shulman's model, it also provides insights into the participants' conceptual understanding as this forms the basis of the former[11]. While the focus in each stage *is* different, the data forms a coherent single data set for the reason above. Additionally, each stage addresses various aspects of the same set of design parameters for content and context.

The following sections describe the details of the items in the above tables, define the parameters to be investigated, and discuss aspects of the data collection process and the approach taken in data analysis.

11. as discussed in Section 3.1.

5.6.2 Parameters for investigation

The content-focus of this study is on the participants' knowledge (content and pedagogical) of gravity and gravitational fields in terms of the contexts and content of the VCE physics syllabus (see Section A.1 on page 1 for details of the curriculum, assessment, and work requirements). As such, the parameters for investigation are drawn from that VCE unit 4 context and content as in Table 5-5.

Table 5-5: Methods employed to probe specific curriculum areas

Curriculum focus area	How it was probed
1. Newton's law of universal gravitation ($F = GM_1M_2/r^2$).	This is implicit in all of the probes used in the study but only explicitly manifested in the 'planetary' probes where the effect of the mass and separation of masses could be examined in a variety of situations.
2. Circular orbits under gravity (using $a = v^2/r = 4\pi^2r/T^2$, comparison with non-circular motion using straightforward energy concepts).	The 'planetary' probes were used to explore the subjects' notions of orbital motion from several perspectives: Satellite capture. Gravitational deflection. The 'slingshot' effect.
3. Gravitational field ($g = G M/r^2$).	All probes were designed to raise situations in which gravitational field could be raised by the subjects. The planetary probes provided the most explicit cases where this was likely to be raised, as explaining the motion of objects in them required an understanding of the nature of the often complex gravitational fields they were moving in.
4. Weight, apparent weight (mass and weight as measured by the normal reaction N, experience of weightlessness when N = 0).	Video clips of 'The Simpsons' and the 'Road Runner' contain multiple instances of discrepant events on weightlessness and free-fall.
5. Energy transfers from area under force-distance graphs.	This was not included in this study as it was considered to be essentially mechanistic, and did not relate explicitly to the field and gravitational contexts under examination.

Further probing through the use of the FCI provided an independent snapshot of the subjects' understanding of the Newtonian force concept (which underpins all of the above) across six conceptual areas as described in Section 6.3 on page 187.

5.6.3 *Methods of data collection*

Data collection was by means of a clinical interview (in two stages) as described above, and a multiple-choice instrument — the Force-Concept Inventory. These are described in detail in the next chapter. They were adopted for several reasons. Firstly they were an efficient means of gathering the relevant data. This was an important consideration as approval to conduct the research was based on it placing little real burden on the participants, and also to a lesser degree, because there were limited opportunities to meet with the participants as they were on a complex, individualised timetable (this was to cause difficulties in scheduling interviews, and in a number of cases, required the interview to be conducted over more than the two planned sessions), The multiple-choice instrument could be completed by the subjects in about 40 minutes under controlled conditions — it was completed by them in my office during stage one of the research. The instrument was a widely used and validated one. The data would provide a general profile of the participants' understandings of the Newtonian force concept, which underpins all of the mechanics concepts in the VCE physics unit that was being examined. The larger clinical interview was likewise conducted in my office during stage two of the research. This was an appropriate method to use to gather the participants' reactions to video-clips and computer simulations as it involved extensive discussion about the nature of the various events in the study.

In stage 1.1 the initial participant data were entered by hand on to a prepared printed form. The multiple-choice instrument used in stage 1.2 was produced as a web-based form, allowing the participants to enter their answers quickly by selecting them from 'pop-up' menus. This led to a significant time saving over the time taken in trials using printed booklets and response sheets — from an average of 34 minutes to 24 minutes. NetForms™ (MAXUM, 1996) was used to automatically convert the form data to a tab-delimited text file on the server, from where it was subsequently retrieved and imported into a Microsoft Excel spread sheet for analysis.

The participants' responses to the 'visually clued'[12] field-dependence probes in this first stage were entered directly into a word processor by the researcher, as the amount of data was moderate, and the rate of typing did not significantly impede the progress of the interview. The visually-unclued probes were incorporated into the interview in stage two[13], where they fitted seamlessly into the planetary gravitational probe sequence. The audio transcripts were transcribed into electronic format, and a content analysis (i.e. for content knowledge) was conducted to look for conceptual issues in the data. This consisted of identifying and categorising the conceptual issues that were found in the data.

Roschelle's (1991b) iterative approach to analysing the data was adopted, so that hypotheses were formulated from the data, and then revisited several times by means of examining the related segments of 'evidence' on the video tapes in an attempt to identify weaknesses and discrepancies in the hypotheses. This pragmatic approach was adopted for its ease of use with the data from this study, and because of its relevance to a study. Unlike the 'constant comparison' approach (Glaser & Strauss, 1967; Mousley & Sullivan, 1998, p.244), this approach is not seeking to

12. see Section 6.4.1.1 on page 195 for details of these items. Section 6.4.1 provides an overview of their purpose.
13. except where participants' time constraints dictated otherwise, when a subsequent short session was held.

generalise across the group of participants, but focuses on each individual's data and in developing an understanding of the individual case. This was important because each individual's pedagogical strategies[14] and mental models are axiomatically idiosyncratic and individual (although perhaps having been constructed through socially constructed process).

5.7 Reconciling the data

The quantitative data resulting from the FCI were not subject to an extensive statistical analysis because the FCI was not developed to be a statistically reliable instrument, but rather, to indicate the agreement between the NFC and the users understanding of it. In addition, it provides insight into areas of mechanics with which the participants might have particular forms of misconceptions. In this study, FCI data are used to develop profiles of the subjects' understandings of the NFC in order to have some baseline data from which to develop further insights into the subjects' conceptual understandings of gravity in the VCE context. As such, the FCI serves as a trialed and validated reference point (but not in a statistical sense) that may provide support for statements and assertions about the subjects' responses to the other probes employed in this study. In this role, the FCI data that describes the subjects' understandings in each of the six categories is only considered as indicating *potential* conceptual problems in those areas generally. The further probes used in this study develop the examination of these in detail only in the context of the specific gravitational scenarios developed for this study.

14. i.e., metaphors, analogies, etc. as in Shulman's model

5.8 Approach to analysis

The aim of the data analysis for this study is to both identify, and to locate within a theoretical model, issues about the ways in which T-PCK (as sampled by the discourse collected in the interview) is used, and its relationship to the participants' (Physics) subject matter knowledge. With the free-text responses from the semi-structured interviews, it was hoped to be able to use Self-Organising-Map (SOM) software (Kohonen, 1995; Kohonen, Hynninen, Kangas, & Laaksonen, 1995) such as Viscovery (Eudaptics, 2000) or WebSOM (Kohonen, Hynninen, Kangas, & Laaksonen, 1998) to facilitate this by visually relating[15] segments of transcripts that contained closely related dialogue, thus assisting the identification and analysis of similar an different response types (cf. Card, 1996; Catarel, 1996; Gershon & Brown, 1996a, 1996b). Unfortunately, desktop SOM software for 'free text' analysis has not yet been developed to a satisfactory state[16] (cf. Lemke, 1998, p.1180), and so the hope of producing a rich graphic visualisation of the data set was set aside, to be replaced by NUD•IST.

NUD•IST was used to analyse the data from these two different perspectives, each using a different analytical strategy. NUD•IST belongs to the genre of textual analysis programs that employ text-unit coding[17] (Fielding & Lee, 1991, p.5), and that support indexing and the creation of a hierarchical index (whilst also supporting non-hierarchical structures — free nodes) to facilitate the cross-referencing and

15. SOM software adopts 'learning vector quantization' to spatially arrange data sets (on a graphic display) according to their similarity — as determined by the context (cf. Honkela, Leinonen, Lonka, & Raike, 2000; Kohonen, Hynninen, Kangas, Laaksonen, & Torkkola, 1995).

16. i.e., without an enormous amount of pre-processing and creating reference documents for each data set item.

17. Any section of text within a document may be 'coded' with any number of associated descriptive terms.

retrieval of text-units from a collection of documents which, in this study consisted of the transcripts of the participants' responses and personal data collected in the phase one interview, their FCI data, and responses to the video-clips and computer-based probes in phase two.

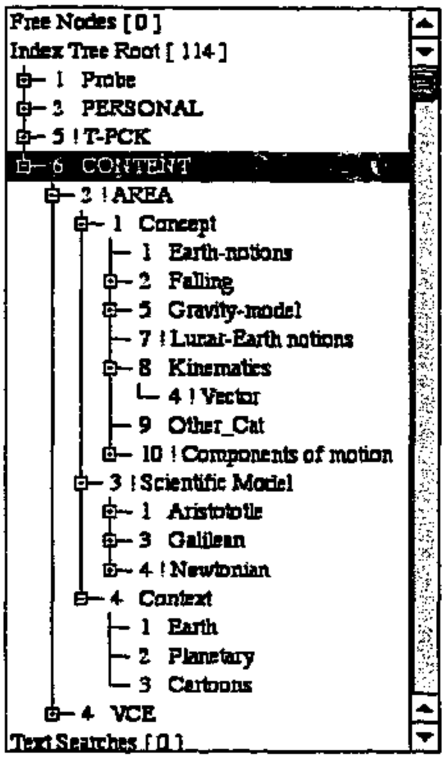
In order to examine the participants' content knowledge of the specific gravitational contexts, a semantic content analysis (Lemke, 1998, p.1180) was conducted, based on the Newtonian concepts, historical models, and misconceptions reviewed in Chapter 4. An analysis of the participants' discourse was anticipated to reveal aspects of their PCK. A synthesis of the two sets of findings was anticipated to reveal significant aspects that would inform the development of a knowledge base for this topic that could inform some aspects of the development of PCK-enhanced software.

5.8.1 Content knowledge index

The Newtonian index was developed from both the content of the VCE curriculum, and from the review of the research literature in Chapter 4. It consisted of both specific content of relevance to the VCE physics curriculum, and more inclusive items on Newtonian mechanics, and categories of common misconceptions.

Participants' transcripts were examined and coded according to the Newtonian index structure. Text-unit encoding was done at the sentence level so as to capture 'units of meaning' (Harrington & Oliver, 1999, p.11) rather than individual words or phrases. Many text-units were multiply coded, as they fitted into a number of categories in the index. NUD•IST readily supports such multiple coding. However, the ability to code specific items to a fine level of detail (in a NUD•IST sub-node) has the potential to fragment data that may be functionally coded at a more general level — a 'forest or trees' issue. Cannon (1998, p.4) comments on the need for a 'sensitive methodology' to ensure that complexity is maintained, '...without representing the problem as too vast to identify action'. For example, subtle variations in thinking about, say, radial acceleration during orbital motion, while of great academic interest, may not necessarily be significant within the context of the research question. Thus there is a pragmatic conceptual design issue in generating the index to ensure that the granularity is appropriate and functional, but not necessarily too detailed so as to fragment the focus. It is, however, also possible to adopt the position that data coded below any given (hierarchical) node can be effectively aggregated using NUD•IST's report feature, and so it may well be worthwhile to develop a highly detailed index. The level of detail to which any particular index needs to be created depends on the nature of the research question, the level of detail provided by the source materials used, and the resources available to create it. In this thesis, this means categories that generally match the physics content areas of the VCE curriculum area of interest to this study — with participants coded against areas that aggregate a number of items, such as those detailed in Section 4.2.2.4 on page 95, Section 4.2.3.2 on page 102, Section 4.3.2.1 on page 110, and Section 4.3.3 on page 111. In addition, further items identified in the literature review were also included when and where they either formed a new index component, or fitted within the definition of an existing index category (as a further example or context).

Figure 5-4: The initial content knowledge NUD•IST index employed in this thesis (to level 4)



5.8.1.1 Cross-coder reliability - content knowledge

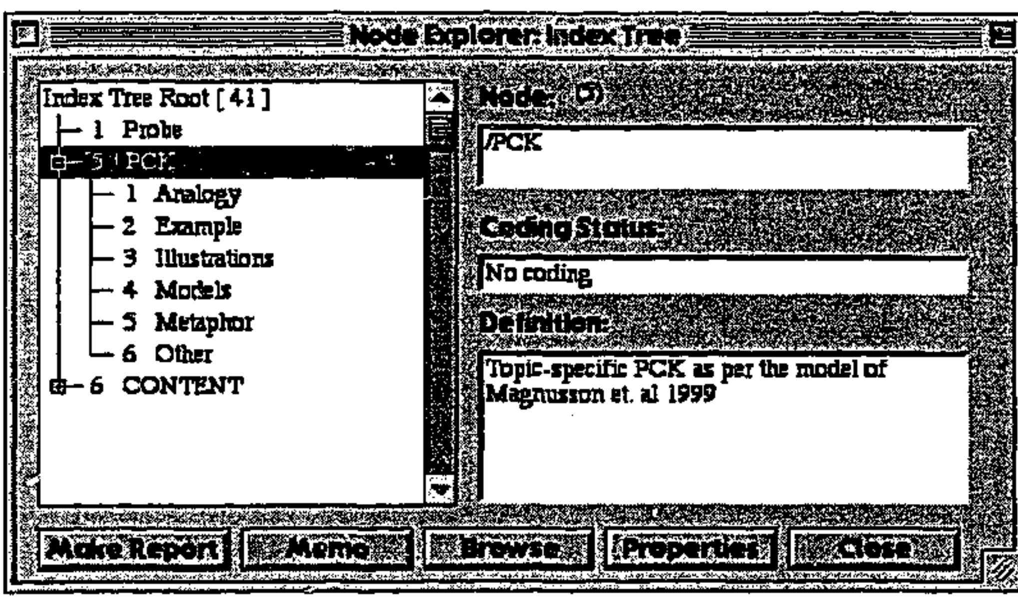
The index nodes created for content knowledge analysis (as in Figure 5-4) have explicit links to the literature as depicted in Figures 4-2 to 4-17, and so *a priori*, may be expected to have a high cross-coder reliability provided that they are used correctly, meaning that the coder has applied them correctly[18] and consistently across the data set. The adoption of general categories such as Aristotelian, Newtonian, etc. helps in this regard be aggregating a plethora of possible observations under a more inclusive, and (hopefully) more robustly defined terms, hence potentially limiting errors in assigning data to categories.

18. i.e., consistent with their use in other studies

5.8.2 PCK index

The T-PCK model adopted for this thesis is based on that of Magnusson, Krajcik, & Borko (1999), with the additional categories of metaphor and 'other' added at the level of representation as discussed in Section 3.2.1[19]. These items form the six-node NUD•IST index structure for T-PCK (Figure 5-5) that was used in the analysis of participant data.

Figure 5-5: The PCK NUD•IST index employed in this thesis (adapted from Magnusson et al., 1999, p.99)



5.8.2.1 Cross-coder reliability - PCK

In order to maximise consistency in coding, independent verification of the accuracy of coding was conducted by an external reviewer. This was felt to be necessary because of the lack of published examples of T-PCK (unlike the content knowledge coding) that could be related to this study, and the need to ensure that

19. see also Figure 2-1 on page 24

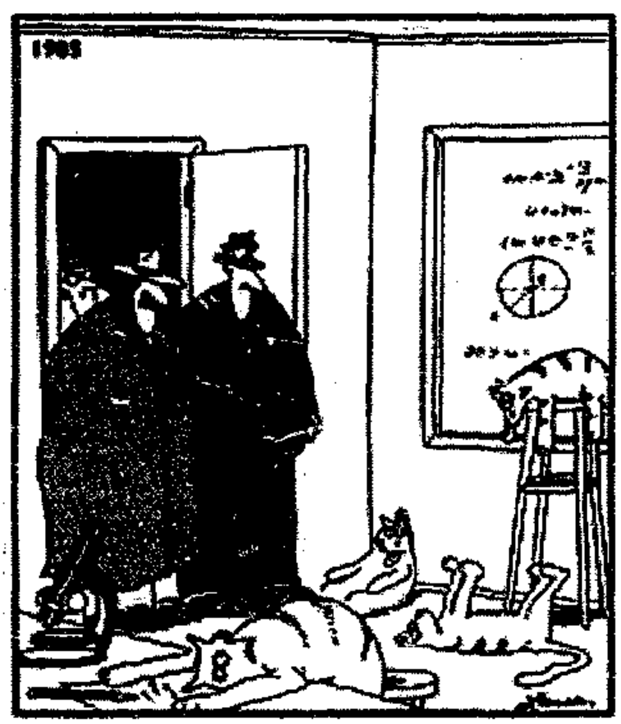
the coding was applied consistently according to the coder definitions. The initial coding was done by the researcher, and subsequently reviewed by the external reviewer in conjunction with the researcher. This took the form of interactive sessions in which the researcher was required to justify the appropriateness of the coding, and to demonstrate the consistency of the coding. Items that were in dispute were resolved by discussion between the reviewer and researcher.

5.9 Chapter Review

This chapter addressed the methodological aspects of the interview-based research for this study, reviewing the rationale for the chosen methodology, describing the aims and origins of the research, the processes and issues that shaped the final research design, and providing a justification for the use of a case study methodology. Procedural and methodological aspects of research interviews of relevance to this study were reviewed. The chapter concluded with a description of the interview protocol, and the approach to data analysis, for both subject matter knowledge and PCK.

Chapter 6

The research instruments



"Notice all the computations, theoretical scribblings, and lab equipment, Norm. ... Yes, curiosity killed these cats."

6

The research instruments

> The use of technology is so common that to compare its use to current nontechnological practice would be equivalent to comparing instruction with books to the same amount of instruction without books 20 years ago.
>
> (Berger, Lu, Belzer, & Voss, 199[illegible], p.486)

6.1 Data collection

This chapter discusses the nature of the instruments used in the participant-interview phase of this thesis that seeks to examine their subject matter knowledge and T-PCK in the selected context[1]. It comments on the design, usage, and methodological issues involved in completing the student-data collection and related methodology. It begins with a description of the data collection methods. This is followed by a discussion of the rationale for the design and adoption of the various probes used in this thesis. The actual probes, and the software[2] required to run them[3], are included on the associated CD-ROM[4].

In this discussion, for each probe, an explanation of the nature of the probe comes first in the text, followed by a rationale for its adoption. Where a series of similar probes are used together, wherever possible, the general design details are described in this chapter, with further details of the series provided in the appendices

1. as discussed previously e.g., Chapter 2
2. The majority of the software requires a Macintosh Power PC running OS8.1 or later and 64Mb of memory.
3. Except for software where this would contravene the Australian Federal Copyright Act (1999).
4. Both Macintosh (OS 8.6) and Microsoft Windows (Win95/97/98) format CD-ROMS are provided.

commencing at Section A.5, and on the associated CD-ROM.

In order to illustrate the use of these probes, selected indicative[5] quotes from participants in this study are included with the descriptions of some probes. In such cases, the participants are referred to by the pseudonyms as listed in Section 2.6.2 on page 41.

6.1.1 Granularity

In accordance with the discussion in Section 5.4, the instruments focus on a very small slice of gravitational phenomena — those relevant to the VCE context at the heart of this thesis (Section 2.1). In particular it attempts to carefully examine the participants' knowledge and understanding of gravitationally-induced orbital motion (as detailed in Section A.1). The sequence of the probes described below is designed to require the participants to discuss their understandings

6.1.2 Quantitative Data

Quantitative data were collected using an existing multiple-choice instrument — the Hestenes Force-Concept Inventory (FCI) (Hestenes et al., 1992) — 'probably the most widely used instrument in physics education' (Hestenes & Halloun, 1995a, p.502). The FCI is designed to produce '...a general profile of the subject's knowledge of the Newtonian force concept in six categories, each of which has an additional structure' (Halloun & Hestenes, 1995, p.1; Hestenes & Halloun, 1995a,

5. i.e., selected only to show the kind of response that might be expected from the use of the various probes, and not on any particular criteria.

p.503). In this study, the FCI is used to provide a general indication of the students' understandings of Newtonian force concepts, rather than in its more common role of evaluating the efficacy of physics instruction (Hestenes & Halloun, 1995a, p.502).

6.1.3 Qualitative Data

A clinical interview was used to collect qualitative data. This method is one of the most common methods employed in science education research into 'alternative conceptions' (Wandersee et al., 1994, p.200). It was designed as a semi-structured 'interview about circumstances' (Gilbert & Osborne, 1980; Gilbert et al., 1985) that was designed to elicit 'fine grained', detailed data about the participants' knowledge of a series of gravitational contexts. This data complements that gained from the FCI, which 'must be supplemented by information from other sources to get a reliable profile of student understanding.' (Halloun & Hestenes, 1995, p.2)

The interviews required the participants to respond to events embedded in video-clips, and to interact with computer simulations that were created for this study by the researcher (see Section 6.1.4 on page 178 for the principles informing their development). These were validated, and modified where necessary, prior to use by trialing them with a number of students and staff from the Faculty of Science and Technology.

The video-clips acted as stimuli for the participants to discuss the embedded physics in an attempt to have the them reveal the nature of their explanations, analogies and metaphors[6] — aspects that might shed light on the nature of their T-PCK and content knowledge. The series of graded computer-based probes explored aspects of their understandings of the physics of orbital motion and planetary physics. Each of the computer simulations were used in either a 'predict-observe-explain' model (Bliss, 1989, p.266) or as discrepant events (Fensham & Kass, 1988). The interview was audio-taped, and the participant's responses to these probes were video-taped. The data were then coded and indexed in a NUD•IST database[7] for subsequent analysis.

6.1.4 A principled approach to probe development

The development and selection of the interview probes forms part of the research for this thesis. This section describes the principles and processes that informed the development of the probes developed specifically for this thesis[8] (as described in Section A.5), and discussed in this chapter. The rationale for use of the FCI is discussed below in Section 6.3.

6.1.4.1 FIELD-DEPENDENCE PROBES

Visual complexity has a number of dimensions that are relevant to this study, as discussed in Section 6.4.1. Rotater™ (Kloeden, 1995) allowed the ready creation of a 'rod and frame' environment (Shipman & Shipman, 1985, p.233) for rectilinear motion in which participants could observe particles moving through a three-dimensional, rotatable cube which allowed them to inspect the motion from any

6. See Section 3.2.1 on page 62 for a discussion of representational formats.
7. as described in Section 5.8.1 and Section 5.8.2.
8. i.e., exclusive of the FCI.

angle. The focus of these probes is to see if the participants can both interpret the motion in the cube, and relate it to the presence or absence of gravity. A graded sequence of five probes was developed for this purpose as described in Table 6-1.

Table 6-1: Areas of focus of the 3D Rotater™ field dependence probes.

Area	Probe	Focus	Rationale
1	1 2 3	Uniform linear motion depicted as motion along the X, Y, and Z axes respectively.	Standard representations of uniform motion form a 'baseline' from which accelerated motion can be represented.
2	4	Uniformly accelerated motion in one dimension.	To determine if participants can identify an instance of linear acceleration and relate it to a force or to gravity.
3	5	Uniformly accelerated motion in two dimensions	To determine if participants can identify an instance of non-linear acceleration and relate it to a force or to gravity.

Whereas the probes above contained explicit visual, structural clues, StarLogo (Resnick, 1997) was used to create a series of essentially featureless (in terms of specific orienting features such as a bounding cube) probes as described in Table 6-2

Table 6-2: Areas of focus of the StarLogo field dependence probes.

Area	Probe	Focus	Rationale
1	Green	Uniform linear motion depicted as motion across an indeterminate plane of uniform colour.	Ability to interpret unclued displays and to relate the perceived linear motion to gravity, or its absence.
2	Blue	Both uniform linear motion and accelerated motion depicted as motion across an indeterminate plane of graded colour	Ability to interpret unclued displays and to discriminate between uniform or accelerated motion and to relate the perceived linear and curved motion to gravity, or its absence.
3	Red	Planetary gravitation as employed in many of the other probes in this thesis.	To determine if participants can identify an instance of non-linear acceleration and relate it to planetary gravity.

6.1.4.2 CARTOON PROBES

As discussed in Section 5.4, the use of cartoon probes was based on Hayes' notion of providing students with situations in which the normal laws of science were suspended, in order to challenge their notions of them (cf. Bliss, 1989), and to a lesser extent, because 'cartoon physics' was part of the origin of this thesis[9]. Both chosen cartoons — Homer's leap (FOX Television, 1992) and selected clips from various 'Road Runner' cartoons (TIME Warner, n.d.) — contained a number of events in which gravity was a major factor, while (in accordance with Hayes) suspending the laws of Newtonian physics. Thus they were ideally suited for use as probes for the gravity context of the VCE curriculum.

Table 6-3: NFC items that feature significantly in the video probes (cf. Table 6-6).

FCI content area or item	Homer	RR1	RR2	RR3	RR4
N1	√	√	√	√	√
N2	√	√	√	√	√
N3	√	√	√		
Cancelling forces				√	
Solid contact - passive	√	√			
Solid contact - impulsive	√	√	√	√	√
Solid contact - friction opposes motion	√	√			
Fluid contact - air resistance	√	√	√	√	√
Solid contact - Buoyancy				√	
5G1 Gravity	√	√	√	√	√
5G2 Acceleration independent of weight	√			√	√
5G3 Gravitation - parabolic trajectory	√	√			

9. as described in Section 2.1

6.1.4.3 SOFTWARE PROBES

As discussed previously[10], in addition to the use of rich visual media (see page 151 for a discussion of the methodological considerations), it was originally planned to have the participants actively constructing computer-based microworlds as a major part of the research (cf. White & Horwitz, 1987), but this proved to be impractical[11]. Microworld construction can lead to detailed insights into thinking processes and conceptual understandings because the construction of a microworld results in a concrete representation[12] of part of the constructor's knowledge. Additionally, the rich dialogue between constructors, and between constructors and researchers, can also provide further or richer insights into cognitive processes and understandings (e.g. Adams, 1988; Berger et al., 1994, p.482; diSessa, 1982; diSessa et al., 1991; Lawler, 1979: Ploger & Lay, 1992). In seeking an alternative approach, I sought to keep what I believed, from a researcher's perspective, were the most valuable aspects of microworld construction[13]:

- a sustained engagement with a particular concept or topic that elicits fine-grained, often incremental, data about the constructor's knowledge, and sometimes, about cognitive development processes (e.g., Lawler, 1985; McCauley, 1984);
- production of a 'text'[14] that represents a snapshot of the constructor's knowledge at a particular instant (e.g., Brna, 1989; Weller, 1995);
- the facilitation of rich dialogue about the context under consideration (e.g., Harel, 1991; McDougall, 1988).

10. as described in Section 5.3
11. for the reasons given previously.
12. i.e., in the form of code, structure, and visual representation.
13. but without the use of programming constructs.
14. i.e. a concrete representation.

While all three are interrelated, in the context of this thesis, the latter is arguably the most important. It was desirable that an alternative development environment be able to do all of these things. In particular, it had to be as engaging, interactive, and challenging as microworld construction often proved to be (cf. Harel, 1991), so as to encourage the participants to generate a rich dialogue about the events being depicted. Also, the ability to realistically represent contextual material (whether graphic, text, or video) was desirable[15] (cf. Campbell-Lavoie, 1993) — in a manner similar to that generated by, for example, computer games or virtual reality environments (e.g., Back, 1996; Dede et al., 1996; Osberg, 1997; Swan, 1997; Windschitl & Winn, 2000).

In addition to this demanding list of requirements, it was considered to be essential to be able to gather fine-grained data from the kinds of incremental models or processes that could mimic those that might be created by microworld constructors making small adjustments to their models as their understandings changed. After considerable experimentation, it became apparent that no one software package could perform all of these tasks optimally across the range of intended contexts (see Table 5-2 on page 152).

6.1.4.3 (a) Planetary probes

The intended purpose of these probes was to create a rich dialogue about the planetary events depicted in the probes in order to gain insight of the participants' knowledge of gravity, particularly about N4, related to the VCE curriculum context (Table 2-1 on page 20). In accordance with Bliss' (1989) and Hayes' (1979) use of

15. i.e., as can be achieved in MicroWorlds or StarLogo.

media in probing students' conceptions, not all of the probes were based on realistic contexts, but rather, on complex, multi-object environments that required the participants' to extend their thinking and to apply their knowledge to completely new situations[16]. It was also considered (as in the following section) that some interactivity was desirable in order to engage the participants by providing some 'hands on' interactions with the probes.

StarLogo (Resnick, 1997), MicroWorlds (Silvermann, 1993), and Interactive Physics™ (IP) (Knowledge Revolution, 1992) were all used to create representations of planetary gravity contexts, but none could compete with Gravitation™ (Rommereide, 1988, 1994), a dedicated gravitational simulator, for ease of creation, and the simple but sophisticated user interface that allowed direct manipulation of planetary mass, velocity, and the position of planets. In addition, after running a probe, it allows users to step through the recorded motion (both forwards and backwards), to zoom in or out, and to limit speed so that events which transpire rapidly can be seen more easily. In addition, after running a probe, users can easily modify the mass, velocity, and position of object so as to experiment with the effect of so doing, or to demonstrate a particular understanding or effect.

This series of ten planetary probes has three foci as described in Table 6-4 below. These attempt to provide fine-grained, sequential probing of the core gravitational contexts of the VCE Unit 4 physics curriculum.

16. i.e., other than those they would likely have seen in their physics or physics-education courses.

Table 6-4: Areas of focus of the planetary probes.

Area	Probes	Focus	Rationale
1	1 2 3	Understanding of gravitational field around a single planet.	This is the basic context with which participants are expected to be able to teach in the VCE physics curriculum.
2	4 5 6	Understanding of gravitational field in a binary planetary system.	Explores understanding of superposition and the nature of gravitational fields.
3	7 8 9 10	Understanding of inter- and intra-particle interactions in multi-particle planetary systems.	Explores understandings about N4, (e.g.. effect of mass and distance) in systems composed of objects of vastly different mass

6.1.4.3 (b) Vector probes

These probes were intended to provide the participants with multiple representations of events that they had previously seen only in pictorial format (i.e., as 'bodies moving in space', leaving only a trail to mark their path) in order to further probe their understandings of those events. The use of IP allowed the participants to 'see and feel' (Beichner, 1989) the connection between the graphic planetary events and their formal vector or graphical (i.e, as a graph) representations[17]. Additionally, further representations could be added by selecting appropriate vectors to be displayed, or a by choosing to graph (in a variety of formats) selected quantities against time.

In terms of the criteria discussed at the start of this section, IP provides a number of essential features. At its most basic, microworlds can be preprogrammed and set to 'player mode' so that they can only be 'run' in order to show particular events.

17. While IP can display graphics somewhat similar to those employed in the planetary probes, it was not employed for that purpose because of its complex visual interface, which, it was felt, might distract or intimidate the participants.

However, by using them in 'normal mode' (as opposed to player mode), users can make use of the rich range of visualisation and programming tools to adapt or explore a microworld in detail — making small adjustments (cf. Roschelle, 1991b), and is so doing, become interactively engaged with the microworld. It was anticipated that the discussion around this engaged interaction would be similar to that reported with user-created microworlds (e.g., Adams, 1988; Adams & DiSessa, 1991).

The sequence of five preconstructed probes takes the participant through a series of vector representations of events with which they have previously engaged:

Table 6-5: Foci of the vector probes.

Focus	Probe	Focus	Rationale
1	1 2 3	Understanding of the vector representation of single variables during orbital motion.	Attempts to clarify or extend issues raised in the previous planetary probes.
2	4	Understanding of relationship between several simultaneously displayed vector variables.	Attempts to determine if the participants have a clear understanding of the relationship between dynamic and kinematic vector quantities.
3	5	Understanding of inter- and intra-particle interactions in multi-particle planetary systems.	A 'post test' probe to see if participants can demonstrate their understanding, or interpret complex events when presented in a vector representation.

The first three probes present a single vector — either gravitational force, instantaneous velocity, or acceleration. All three were included in the fourth probe so that their relationship is explicit to the participants. The fifth probe presents a new context for the participants to their understandings of planetary gravitational interactions gleaned from the previous four probes.

6.2 The Preliminary Questions

Basic personal data were collected: contact details, and levels of educational achievement in a range of sciences — the latter to determine their educational background in the sciences as it was felt that this data would be useful in identifying the extent of their engagement in formal science studies. This was a potentially significant item, as the possibility existed that some of the participants may have taken a physics method course as their third option in conjunction with a double-major study in another area, such as Drama or Physical education, with Science as a minor academic study[18]. In such cases, participants may have met the entry requirements to the course with a pass in a VCE science subject at year 11 or year 12 — not both as is the usual requirement for a normal major-minor combination.

With the particular grouping of units in the VCE physics curriculum, participants who had not completed the full sequence of units could have missed out on learning some key concepts and major areas of physics. This could be expected to have an impact on their subsequent conceptual development at University, and on their ability to teach some aspects of physics. The participants were also asked to give a self-assessment of their general physics knowledge, and of their understandings of mechanics.

18. See Section 2.6.1 for an explanation of course options available to the participants of this study.

6.3 The Force-Concept Inventory

The Force Concept Inventory[19] (FCI) is a multiple choice instrument that was designed and validated to 'measure the disparity between student concepts and the Newtonian force concept' (Hestenes & Halloun, 1995b, p.502), or put more generally, 'the FCI score is a measure of one's understanding of the Newtonian Force Concept'. (Hestenes & Halloun, 1995a, p.504). Developed from the more general Mechanics Baseline Test (Hestenes & Wells, 1992), it was produced to help teachers probe and assess their students' 'common sense' beliefs by requiring students to make a choice between Newtonian concepts and common sense alternatives (Hestenes et al., 1992, p.142). There is only one correct Newtonian answer to each question. The FCI is not an exhaustive instrument, but rather one that indicates areas of student difficulty with the most basic concepts of Newtonian mechanics.

The focus on the Newtonian concept of Force as an indicator of the level of understanding of Newtonian concepts is due to the centrality of force in Newton's formulation of mechanics[20]. Use of the instrument results in a profile of the students' understandings of force in each of six categories deemed by the authors as essential for a coherent understanding of the Newtonian force concept (see Table 6-6 on page 189). The six concept areas are meant to be the minimum required to allow the instrument to reliably determine students' level of Newtonian thinking (within the confines of the scale). Gravity is included under the category of 'kinds

19. see Section A.3.
20. see Section 4.3.1.

of forces'. Wide spread FCI use has demonstrated its effectiveness in this role. Halloun and Hestenes caution that in interpreting FCI data, it is essential to note that it was '...never intended to describe student concepts. Rather it describes the Newtonian standard against which student concepts can be compared in detail.' (Halloun & Hestenes, 1995, p.2) The designers also claim that the FCI can also be used to diagnose 28 specific misconceptions about the NFC by analysis of the students' incorrect responses to the FCI questions (Hestenes & Halloun, 1995b, p.504). Not all incorrect responses, however, correspond to recognised 'misconceptions'. Table 6-7 on page 190 shows the taxonomy of student misconceptions[21] suggested by responses to items in the FCI. To facilitate comparisons with the Newtonian responses, Table 6-7 is organised into the same six categories as the FCI. Hestenes and Halloun (1995b, p.506), however, caution that 'We do not claim, however, that these categories describe conceptual structures of individual students.'

21. the authors (of the table) term.

Table 6-6: Correct responses for Newtonian concepts in the FCI; a parenthesis means that other concepts are significantly involved in choosing the correct response (after Hestenes et al., 1992, p.142).

Newtonian concept area	Correct response
0. KINEMATICS	
K0.1 Velocity discriminated from position	20E
K0.2 Acceleration discriminated from velocity	21D
Constant acceleration entails:	
K0.3 parabolic orbit	23D, 24E
K0.4 changing speed	25B
K0.5 Vector addition of velocities	(7E)
1. FIRST LAW	
NI.1 with no force	4B; (6B); 10B
NI.2 velocity direction constant	26B
NI.3 speed constant	8A; 27A
NI.4 with cancelling forces	18B; 28C
2. SECOND LAW	
N2.1 Impulsive force	(6B); (7E)
N2.2 Constant force implies constant acceleration	24E; 25B
3. THIRD LAW	
N3.1 for impulsive forces	2E; 11E
N3.2 for continuous forces	13A; 14A
4 SUPERPOSITION PRINCIPLE	
S4.1 Vector sum	19B
S4.2 Cancelling forces	(9D); 18B; 28C
5. KINDS OF FORCES	
5S - Solid contact	
5S1 Passive	9D; 12B; 12D
5S2 impulsive	15C
5S3 Friction opposes motion	29C
5F - Fluid contact	
5F1 Air resistance	22D
5F2 Buoyant (air pressure)	12D
5G - Gravitation	
5G1 Gravitation	5D; 9D; (12B,D); 17C; 18B; 22D
5G2 Acceleration independent of weight	1C; 3A
5G3 Parabolic trajectory	16B; 23D

Table 6-7: FCI-inferred misconceptions. A misconception is suggested by the selection of the corresponding Inventory item (after Hestenes et al., 1992, p.144).

Misconception	Inventory item
0. Kinematics	
K1. position-velocity undiscriminated	20B,C,D
K2. velocity-acceleration undiscriminated	20A; 21B,C
K3. nonvectorial velocity composition	7C
1. Impetus	
I1. impetus supplied by "hit"	9B,C; 22B,C,E;29D
I2. loss/recovery of original impetus	4D; 6C,E; 24A; 26A,D,E
I3. impetus dissipation	5A,B,C; 8C; 16C,D; 23E; 27C,E, 29B
I4. gradual/delayed impetus build-up	6D; 8B,D; 24D; 29E
I5. circular impetus	4A,D; 10A
2. Active Force	
AF1. only active agents exert force	11B; 12B; 13D; 14D; 15A,B; 22A;29A
AF2. motion implies active force	29A
AF3. no motion implies no force	12E
AF4. velocity proportional to applied force	25A; 28A
AF5. acceleration implies increasing force	17B
AF6. force causes acceleration to terminal velocity	17A; 25D
AF7. active force wears out	25C,E
3. Action/Reaction Pairs	
AR1. greater mass implies greater force	2A,D; 11D; 13B; 14B
AR2. most active agent produces greatest force	13C; 11D; 14C
4. Concatenation of Influences	
CI1. largest force determines motion	18A,E; 19A
CI2. force compromise determines motion	4C; 10D; 16A; 19C,D; 23C; 24C
CI3. last force to act determines motion	6A; 7B; 24B; 26C
5. Other Influences on Motion	
CF. Centrifugal Force	4C,D,E; 10C,D,E
Ob. Objects exert no force	2C; 9A,B; 12A; 13E; 14E
Resistance	
R1. mass makes things stop	29A,B; 23A,B
R2. motion when force overcomes resistance	28B,D
R3. resistance opposes force/impetus	28E
Gravity	
G1. air-pressure assisted gravity	9A; 12C; 17E; 18E
G2. gravity intrinsic to mass	5E; 9E; 17D
G3. heavier objects fall faster	1A; 3B,D
G4. gravity increases as objects fall	5B; 17B
G5. gravity acts after impetus wears out	5B; 16D; 23E

6.3.1 Validation and reliability

The FCI has been used as a pre- and post-test instrument with over 10 000 students at both school and University level (Richard R. Hake, 1994; Hestenes et al., 1992, p.146). Huffman (1993, p.139) considers it to be the 'best test currently available'. They also claim that there is a high correlation between incorrect responses and the existence of a related misconception. Dykstra however considers the FCI to be, '...inferior to the motion and force conceptual evaluation developed by Thornton and Sokoloff, and argues that the 'FCI has been very good politically but its probe is very shallow' (Dewey Dykstra, Jr., personal communication, October 14, 1998). From this perspective, the widespread adoption of the FCI is likely to be more a result of its publicity, rather than its inherent value as a cognitive probe. Intriguingly, the results of some such studies have been used as indicators of physics-teacher competency (Hestenes et al., 1992, p.146), which may be at odds with some aspects of the constructivist perspective that implicitly underpins the instrument.

6.3.2 Gender issues

Until recently there has been little published concern for gender issues in regard to the FCI. Jackson described an apparent gender bias in the related Mechanics Baseline Test (J. Jackson: personal communication, Oct. 28, 1998), and reported on gender studies of the FCI in Asian and Western contexts that suggested that there are no significant gender differences in the Asian countries studies, but that gender differences are significant and consistent in Western nations (Jackson, 1998)

Possible reasons as to why Western nation females score lower (than males) on the FCI post-test were suggested to be that:

- they have more misconceptions;
- they have a poorer background in physics;
- the FCI is a (culturally) biased test.

The extensive electronic discussions that followed on PhysLrNr[22] indicated that there is considerable uncertainty in the physics education research community about the nature and origins of gender issues in regard to the instruments such as the FCI (e.g. Jackson, 1998).

6.3.3 Rationale for adoption

Because it has been extensively trialed, reviewed and 'validated', the FCI has the *status* of a robust and widely accepted instrument, that provides some reliable indications of general student understandings of Newtonian mechanics. In this thesis, the FCI has been adopted to provide a general profile of the participants' understandings of the NFC (see Table 6-6), and to suggest possible categories of misconceptions (see Table 6-7). The data from the FCI is used only as a indicator of the participants' ability to apply a Newtonian viewpoint to mechanics problems, and of their likely misconceptions of aspects of the NFC.

22. The Physics Education listserv electronic discussion area at physlrnr@listserv.boisestate.edu

6.4 Interview Probes

With the exception of the video-clips and field-dependence probes, the probes in this section employ a 'predict-observe-explain' methodology in a range of specific gravitational contexts. To participants' with good understandings of the Newtonian model, the responses to these probes should be obvious, and relate essentially to an understanding of Newton's laws of motion and of universal gravity[23] (i.e., effect of mass and distance) and the related gravitational field structure. In the case of the 'multi-asteroid' probes (Section 6.4.4.2 (g) - 6.4.4.2 (j)), such participants should be able to readily identify the gravitational forces arising from the major mass in each probe, as well as between the asteroids depicted in them. The 'vector probes' (Section 6.4.4.3) likewise present such students with 'obvious' Newtonian representations of Force (including gravitational force), Velocity, and Acceleration.

6.4.1 Field dependence-independence probes

Field-dependence, a particular cognitive style[24], may be an issue in computer-based environments that require users (e.g., learners) to recognise discrete elements in a complex visual display (e.g., Ausburn & Ausburn, 1978; Myers, 1997), because it affects the extent to which learners interact with media, or their ability to make what is depicted meaningful to them (cf. Dwyer & Moore, 1991; MacKay, 2000, p.77). It was considered to be a potentially important issue in this thesis because of the extensive use of visual media in which the participants are expected to identify and

23. See Section 4.3.2 on page 109.
24. see Riding and Rayner (1998) for a detailed discussion of cognitive styles and learning styles.

describe the motion of objects moving in complex visual fields. Therefore their ability to have, '...facility in differentiating objects from embedding contexts...' (Shipman & Shipman, 1985, p.231) is essential for them to be able to engage successfully with the probes.

Field dependence is routinely assessed by the group-embedded figures test (GEFT), or variants of it (Shipman & Shipman, 1985, p.231-233). In this study, I have attempted to gain an indication of the significance of field dependence in its original formulation — the importance of contextual physical clues in learners' ability to understand and describe physical phenomena such as projectile motion by identifying or relying on visual or gravitational clues in determining the 'upright' in space, such as assessed with the Rod-and-Frame Test (Shipman & Shipman, 1985, p.233; Witkin & Goodenough, 1977). Field-dependence may affect the participants' ability to correctly discuss and explain the planetary situations that this thesis is concerned with for two reasons. First, in teaching about planetary motion, the existence of radial gravitational fields requires participants to either constantly adapt notions and descriptions of 'up' and 'down', or to switch to a radial frame of reference which is distinctly different from those used in other mechanics topics in the VCE curriculum. Second, the lack of visible frames of reference (e.g., trees, people, sky) in these probes, particularly three-dimensional ones, may make it difficult to analyse or describe the motion being shown.

This issue was examined through the use of two sets of probes, one of which had an explicit (but not absolute as in 'up' and 'down') frame of reference (visually clued) in the form of a visible bounding cube which has similarities to Witkin's 'Rod and Frame Test' (Shipman & Shipman, 1985, p.233), and one which employed an ambiguous coloured background and no obvious bounding structures (visually unclued). There was no intention to employ an experimental design to test this as these probes are exploratory, seeking only to develop an indication of the potential significance of field-dependence in computer-based contexts such as those employed for this thesis.

6.4.1.1 'Visually clued' probes

This sequential series of five probes allow the participants to study the motion[25] of particles in a virtual cube from any perspective in a simulated three dimensional space. The strong visual clues — the visible cube and the different colours of each edge — as to the nature of the space potentially constitute a reference frame for field-dependent subjects. This is a key feature of these probes. Probes one to three examine uniform motion in one, two and three dimensions respectively, probe four examines linear accelerated motion, and probe five examines curvilinear accelerated motion.

Figures 6-1 and 6-2 depict two of the probes employed in this study viewed from two different perspectives. The probes deliberately have no indication of dimensions, mass, speed or time. It was felt that the omission of these would require the subject to make assumptions about them, and that the range of possible responses would be potentially wider than would be the case with explicit values. This was considered to be an important feature because it allows for several different interpretations, each based on varying degrees of understanding of the relevant physics and the participant's ability to understand the visual model.

25. as depicted by a trail of dots - as in an air-track experiment

Figure 6-1: Example of probe 2

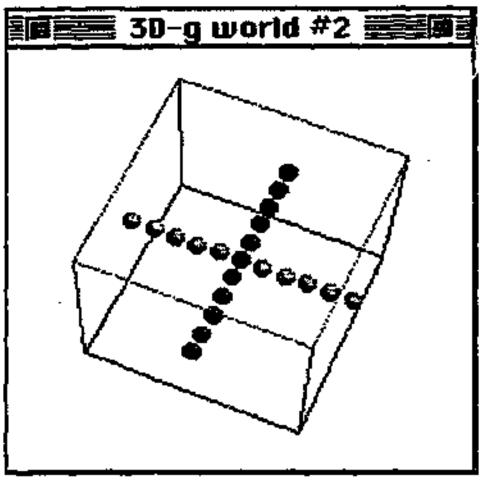
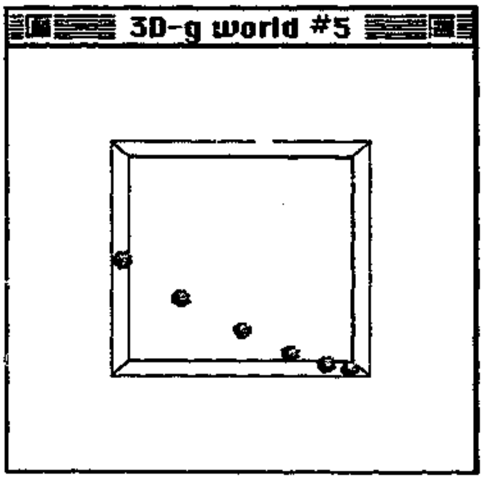


Figure 6-2: Example of probe 5



The following gravitational cases were amongst those considered in this design:

- There is no gravitational field in the cube — in which case the motion will be seen as uniform from any perspective. Probes 1-3 are consistent with this interpretation.
- There a small gravitational field which may be too small to produce an observable acceleration along any axis in the time that the particle is 'in the cube', resulting in negligible visible incremental distances between consecutive points, or negligible deflection of the path — which might depend on the speed of the particle (which is not discernable from the probes). Probes 1-3 are also consistent with this interpretation.
- A large gravitational field may exist in the cube, but the particle may be moving at high speed, in which case it interacts with the field for a very short period of time, possibly resulting in little *observable* acceleration within the time scale, and negligible visible incremental distances between consecutive points or observable deflection. Probes 1-3 are consistent with this interpretation.
- A field in the cube will result in a corresponding acceleration that may, as above, result in a *visible* change in motion. Probes 4 and 5 are consistent with this.

Probes one to three show no obvious change of velocity as the particles move through the cube leaving a uniformly spaced, colinear trail as in Figure 6-1. Probes four and five however show accelerated motion, with probe four depicting linear acceleration in one dimension, and probe five depicting accelerated motion in two dimensions.This display in the first three probes are similar to common air-track and ticker-timer traces for objects moving at constant velocity, and as such, should present little difficulty in interpretation. Even so, they did present challenges to the participants who brought an idiosyncratic range of confounding issues to bear in explaining this seemingly simple motion. Anne[26], for example, relates gravitational acceleration to curvature of the path, possibly related to holding a curvilinear belief (as in Section 4.4.2 on page 121). This is demonstrated in the case of probe one:

Int: And what would that indicate to you?
Anne: That would indicate that its path isn't being bent by gravity, so it's not accelerating or decelerating.

(participant Anne)

and again with probe five:

Anne: Ok so it's being projected off a cliff or something and falling – if we put it in an Earth example. So gravity is acting because it's going down, otherwise it would just go straight across, So it's falling, and it's also accelerating… because the distance between them, those spots, assuming they are all taken the same distance between them, um, yeah, is getting larger, the distance is getting larger.

(participant Anne)

In both cases, Anne has clearly been able to visualise the events being depicted, and interpreted them in terms of her understandings of the relevant physics, which means, in Ausburn's terms (above), that she is potentially field independent.

6.4.1.2 'VISUALLY UNCLUED' PROBES

These probes provide deliberately ambiguous environments that lack explicit structural clues, consisting of a coloured background (uniform or gradient) over which particles appear to move. The 'space' represented by the coloured region may be regarded as two-dimensional or three-dimensional depending on the viewer's

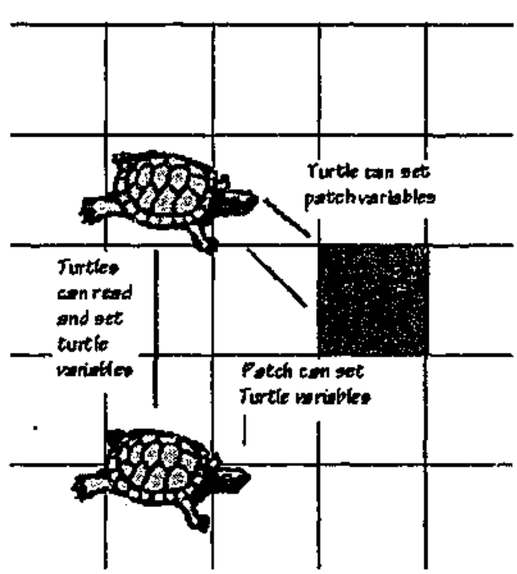
26. as per Section 6.1, participants and their quotes are identified by their pseudonym. (cf. Section 2.6.2)

interpretation of the probe.

6.4.1.2 (a) Development

StarLogo (Resnick, 1992, 1994, 1997) is based on an emulated parallel processing model that supports multiple independent sprites (called turtles), each moving according its own (programmed) laws. 'Patches' are user-configurable sections of the microworld that can be programmed to contain variables and which can interact with turtles moving over them — either setting, or being set by, turtle variables as in Figure 6-3. This allows turtles to respond to values embedded in patches, such as field strength and field direction, allowing turtle motion to be driven by the field model. Such 'field-based' models rely on the ability of turtles to interact with patches, or to sense[27] the other turtles, and to set its own variables accordingly through the use of the NSUM, NSUM4 or sum-of-turtles commands.

Figure 6-3: Turtle - patch interaction in StarLogo



27. meaning to be able to read the values of variables contained in other turtles

This feature provides the ability to create field models by systematically filling in patch values in a way that reflects the desired field. In the probes used here, a gradient was set in the patches, and a visible representation produced by assigning a colour to each patch depending on the magnitude of the gravity variable in each patch, thus producing a gradient colour fill to match the field as in program 6-1. All three probes generate a visual representation of the field model in this way.

Program 6-1: Setting and representing field strength by colour.

```
TO CREATE_HORIZONTAL_FIELD
ca
setdirection 90          ;; field gradient from left to right
SetG 50 + Xcor           ;; field strength is linear function of X coordinate.
scale-pc blue G 1 100    ;; set patch and provide visual representation of left to right gradient
END
```

While this constitutes a visual clue as to the field, it does not provide a structural clue (as in the previous probes) about the space it exists in. The use of 24-bit or greater colour is essential as the resulting colours have a continuous appearance, whereas eight-bit colour images suffer from the appearance of segmentation[28] that may affect the viewer's ability to comprehend the image (e.g., Loula, Kourtzi, & Shiffar, 2000).

Green World is a featureless, green space, that can be interpreted as representing either a 2D or 3D environment (Figure 6-4 to Figure 6-6). The motion of particles in it can likewise be interpreted as either confined to a plane, or occurring in a three-dimensional space. *Blue World* (Figure 6-7 to Figure 6-9) adds a linear gradient fill to the Green World space, in which particles can be observed to accelerate by virtue

28. Examples are provided on the CD-ROM that accompanies this thesis

of the changing distance between the points of the snapshots of their paths. *Red World* simulates a radial gravitational field such as that around a star.

6.4.1.2 (b) Green World

Figures 6-4 to 6-6 show the motion of three particles travelling at different constant velocities. If perceived as a plane, it should be possible to deduce that there is no acceleration in the X or Y directions[29]. This interpretation can be reinforced by the constant motion of the particle travelling diagonally. This is also consistent with interpreting it as a 3D space in which particle three moves into the page (Z-axis). This apparently simple environment is capable of eliciting quite informative responses:

Int: Well, can you see anything that looks like it's being caused by gravity?
Susan: No, the lines are … they are all straight. The dots …are they supposed to be evenly spaced? … Well I think there is no gravity because they are not speeding up or slowing down. The distance between them is always the same… um same distance per unit of time means a constant velocity sort of.
Int: Anything else?
Susan: Well there are no curves.
Int: Curves?
Susan: Like the ones we were looking at earlier.
Int: So gravity always means curves?
Susan: Yes! …Um… except… except when you fall straight down.

(Participant Susan).

29. across the diagram and up the diagram respectively

Figure 6-4: Particle 1.

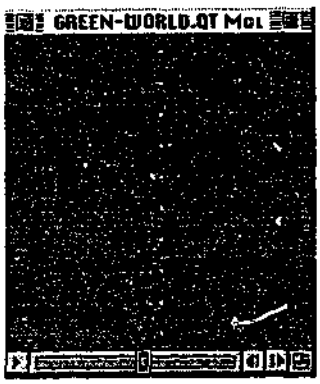


Figure 6-5: Particle 2.

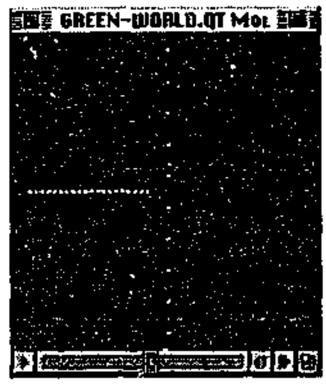
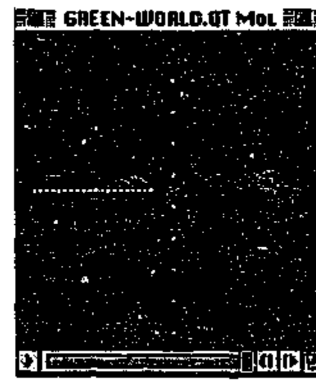


Figure 6-6: Particle 3.



6.4.1.2 (c) Blue World

The colour-gradient can be perceived as representing a slope, or as a clue to the nature of the field that it depicts, which is a 'horizontal' field from left to right.

Figure 6-7: Particle 1.

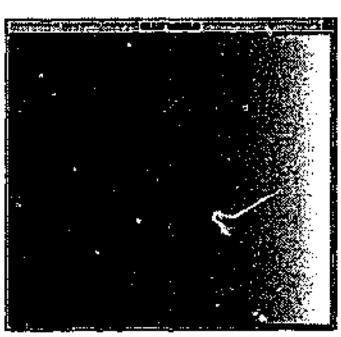


Figure 6-8: Particle 2.

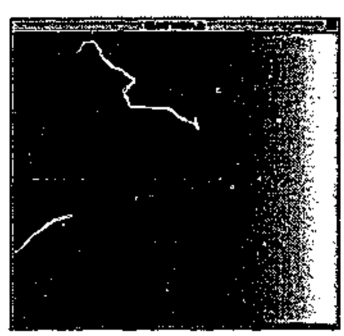
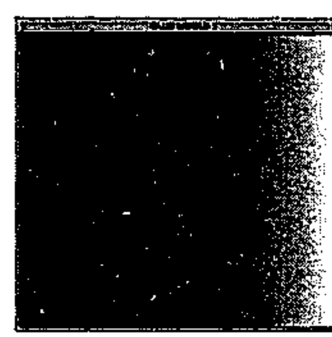


Figure 6-9: Particle 3.



Int: What can you tell me about gravity in that space?
Susan: There is gravity there!
Int: How can you tell?
Susan: Well… the line … the red line curves.
Int: So that's what you were saying before?
Susan: Yes.
Int: What else?
Susan: The red and white lines are spreading out – the dots are moving away too…
Int: So there is gravity there?

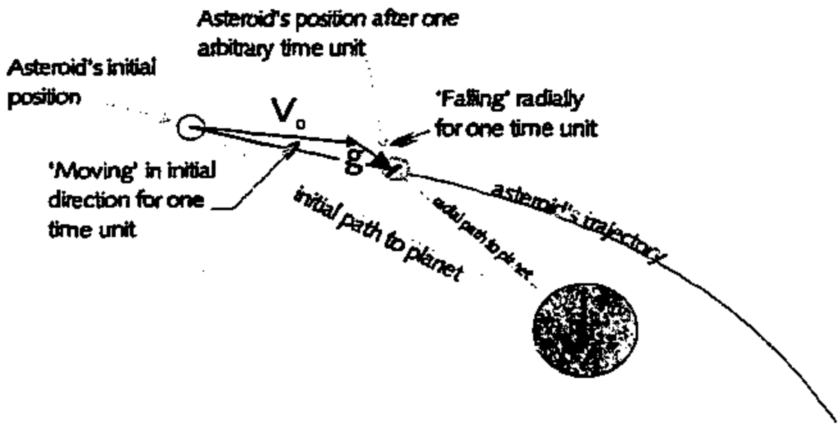
Susan: Yes! It's obvious.
Int: Can you describe the gravity to me? Tell me what it 'looks like' in that world?
Susan: Easy! It's over there on the right hand side!
Int: Why?
Susan: Because the lines are accelerating towards it.

(participant Susan)

6.4.1.2 (d) Red World

Red World, based loosely on Kepler (McCauley, 1984), simulates a planetary system with a radial gravitational field. Kepler focused on modelling the motion of orbiting bodies through the notions of 'moving' and 'falling' — terms that arise from resolving an object's motion into 'inertial' and 'radial' components. Moving is the distance the particle would have travelled in one unit of time had it maintained its initial velocity for that time interval. Falling is likewise defined as the equivalent radial movement of the asteroid towards the planet, again assuming initial radial velocity was maintained. The vector sum of these gives the resultant velocity as in Figure 6-10. This model was used instead of a field-based model because it proved to be more readily scalable than the field-based version (cf. Alexandrov & Soprunov, 1997).

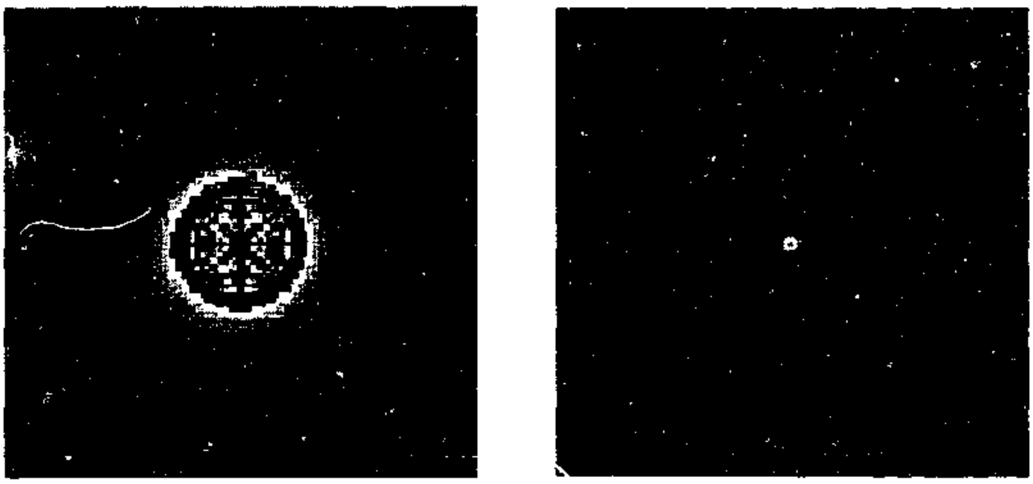
Figure 6-10: McCauley's 'moving' and 'falling' orbital model (McCauley, 1984).



Red World (Figure 6-11) is the first in a series of 'planet-based' probes which are used to explore the participants' understanding of the gravitational context in the VCE physics course. It provides a link between the empty-field representations employed in the Green-world and Blue-world probes, with the presence of an object (planet) in a similar field in terms of environment and representation, and provides a more complex visual environment with which to probe field dependence. Participant Jim, for example, finds it easy to decode the visual information that it contains:

Int: (*Run Red World*) What can you make of that?
Jim: Well there is gravity there because the particles are curving.
Int: So that's proof of gravity?
Jim: Yeah, the gravitational force always um… changes… ah…um bends their velocity vectors.

Figure 6-11: Red World showing 8-bit artefacts (left) and32-bit colour (right).



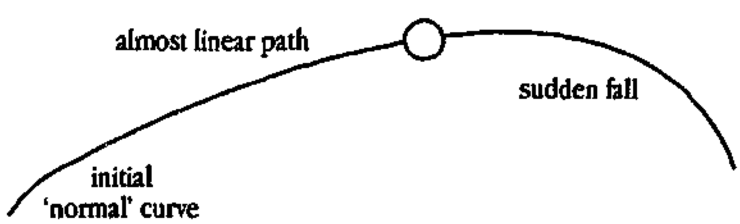
6.4.2 The 'basketball' projectile probe

The basketball probe (Figure 6-12) is an example of the widely employed 'projectile probe' (e.g., Franson, 1996; McCloskey, 1983b; McCloskey et al., 1980; McCloskey & Kohl, 1982; Schnick, 1994) in which the key feature is the parabolic path of the projectile, and the reasons for that specific motion (McCloskey, Kohl, & Wasburn, 1981; Watts, 1982). This probe was used at the start of the interview because it provided the participants with a potentially comfortable and familiar teaching context — 'traditional' projectile motion, with which to commence the interview. It was hoped that this would help to settle the participants, and elicit ready responses in order to commence a dialogue and sense of involvement before moving on to other potentially more complicated situations. In addition, it helps to establish baseline data on the participants' understandings of projectile motion.

While the probe appears, and is, simple in a Newtonian sense, the bio-mechanics of such set shots are complex (e.g., Satern, 1986), and would perhaps be known by those of the participants who are studying physical education. The probe, as such, seemed to offer a useful context in which to explore notions of bio-mechanics, such as 'unweighting' and 'setting', that these participants might bring to their physics classrooms when teaching Newtonian mechanics.

The projectile path is deliberately ambiguous and *similar* to the that generated by an impetus model in order to raise issues in the participant's mind. The initial throw moves the ball upwards, but subsequent motion is essentially linear until almost at the apogee, where the ball falls more rapidly than would be expected without significant air resistance (cf. Figure 4-3).

Figure 6-12: Basketball projectile probe as employed (trajectory only).



A similar trajectory is used later in one of the video probes (Figures 6-17 - 6-19). It also provides a more complex example of projectile motion than those that the participants examined in the FCI. See Section A.5.1 for details of the probe's design and construction. Such a simple probe of what appears to be a well understood phenomenon is surprisingly effective. For example, consider Joanna's response:

Joanna: Ah, no. I'm not very good at this.
Int: Are you able to tell me about the arrows again?[30]
Joanna: I'm sorry. I really am! The gravity down and the gravity reacting from the Earth which is what my teacher in high school explained to me. I never really

30. refers to force arrows previously drawn on a picture of the probe (Figure 6-12).

understood very well myself but I always believed her and it was about something was being ... coming down from the Earth, on to the Earth and the Earth won't move as well. So if something was big enough, it would make the Earth move. I guess like the Sun.

Int: OK. So that's why the basketball moves?

Joanna: That's not why the basketball moves. No. I'm trying to work that out. I can't explain it.

(participant Joanna)

This answer immediately suggests a significant lack of understanding of Newtonian force and gravity concepts, and raises significant concerns about the participants' competency as a physics teacher. Alex, on the other hand, demonstrates both the effectiveness of such simple probes in eliciting understandings, and her ability to relate mathematical and graphical representations in arguing that the motion depicted in the probe, is wrong:

Int: Where does gravity act here?

Alex: Everywhere. Its acting on the ball all the time, pulling it down.

Int: So how does that explain the shape of the ball's path?

Alex: Well, when he throws it, the ball 'falls' because it experiences a gravitational force, and there is no opposing force, so it falls. Hmm it doesn't fall much in the first bit, so maybe its going very fast... but it shouldn't fall there so quickly. I think the picture is wrong.

Int: How is it wrong?

Alex: Well if it is really a normal shot, it would follow the projectile motion ... the equation um ... $S=v_0t + ½at^2$ and then it would be a parabola, because S is the height in this case, and 'a' would be g... gravity ... $9.8m/s^2$. Yeah! So the shape is not symmetrical – see it suddenly falls here and that's wrong. The ball should always be falling. I think this is... a trick picture! It looks as if the ball suddenly hit something, or as if gravity just started acting there.

(participant Alex)

Susan, however, responds almost phenomenologically ...

Susan: Well gravity is acting on all ... on everything.

Int: So its everywhere in there? Always acting on the ball?

Susan: Yes!

Int: Is that why it falls down?

Susan: Yes.

This variety of responses to this simple probe demonstrates the potential of such simple visual probes in eliciting significant information about the underpinning scientific concepts (cf. Bliss, 1989).

6.4.3 Video Cartoon Probes

Cartoons provide a rich source of stimulus materials for science teaching, In many cases, they provide examples of impossible physical events in which the motion of objects, or interactions between bodies, clearly and graphically contradicts the laws of Newtonian mechanics. As such, they provide a rich collection of discrepant events for use in probing understanding of physics. For example, Bliss (1989) used *static* cartoons and comic books in probing students' common sense theories of motion (Hayes, 1979) because of their lack of conformity to a specific model:

> Many studies have used situations similar to school science. We felt it was crucial to avoid tasks which might suggest 'scientific' responses. (Bliss, 1989, p.267)

There is a well articulated literature about 'cartoon physics' which describe the pseudo-laws which apply to cartoons of the genre of the 'Road Runner" series (e.g., Bell, Towheed, & Williams, 1995; Polos, 1995; Toon-D Productions, 1997). The following list is indicative (Bell et al., 1995):

1. A vehicle's speed is limited only by the size of the numbers written on the speedometer.
2. Pretending one is stepping on brakes is as good as having them.
3. Holes are moveable.
4. Impacts against solid objects result in character-shaped holes or indentations.
5. If a tree falls on a character, it results in a partially elastic collision, repeatedly bouncing off their head until they are driven into the ground.
6. It is possible for fire to spread by becoming temporarily animate.
7. A body tends to remain in place or in motion in free space until it notices its situation.
8. All things fall faster than anvils and boulders.

9. Objects launched into the air need not follow parabolic trajectories.
10. Firearms are relatively ineffectual weapons (unless, of course, your intent is to blacken someone's face, make it difficult for them to drink, and hold, water, or remove bills or feathers).
11. Drawings are real as long as you're not aware they're drawings.

6.4.3.1 SELECTION OF VIDEO CONTENT FOR THE VIDEO PROBES

Within the context of a cartoon, the video probes include examples of items found in the FCI, but in different contexts. This was a deliberate choice to ensure that the data from the FCI and that from the video probes would have the potential to be mutually supportive by virtue of covering many of the same items, but in different contexts, and that the static 'pencil and paper' approach of the FCI was complemented by dynamic representations of some of the aspects of specific gravitational motion[31], as well as aspects drawn from across the range of Newtonian concepts included in the FCI. Likewise, the two sets of video probes provide the opportunity to aggregate data about the events they contain, with both having similar events, but which are presented in quite different contexts and scenarios. Table 6-3 lists the FCI items that feature significantly in the various video probes.

6.4.3.2 THE SIMPSON'S PROBE: HOMER'S LEAP

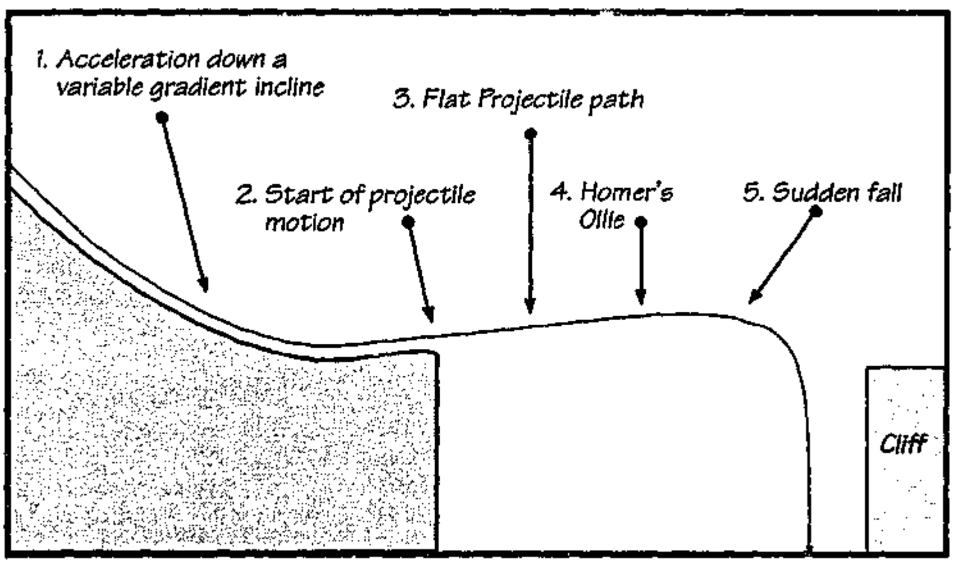
This probe is based on the episode of The Simpsons (FOX Television, 1992) that was observed by 'Suzie' (see page 18). In cartoon format, and in the context of a (cartoon) family problem, it serves as a rich source of relevant physics issues. The scenario in the video-clip contains five segments that explicitly involve gravitationally influenced motion. The key features in the video-clip of Homer's

31. i.e., motion caused by gravitational forces.

leap are depicted in Figure 6-13. Actual screen clips from the video are included later in this section. (see Figure 6-14 - Figure 6-22) and on the associated CD-ROM.

In accordance with the principles of 'cartoon physics' the motion is superficially similar to the expected trajectory, while containing events that are in contradiction to normal physical laws. Many general dynamics concepts (as opposed to explicitly gravitational ones) are embedded within this sequence, but the two cannot be easily decoupled, nor should they be, as an important part of developing an understanding of the participants' knowledge of 'gravity' is to determine how robustly that knowledge is coupled to the underpinning physics concepts, and how it is influenced by the context under consideration.

Figure 6-13: The key features in video-clip of Homer's leap.



The scenario starts with the character 'Homer' on a skateboard, rolling down a steep hill, and about to leap over a deep, wide, gorge[32]. On reaching the edge of the gorge, a slight upwards incline produces an initial trajectory upwards. Subsequently, Homer follows an essentially flat trajectory before suddenly falling. This sequence

32. The video-clip can be viewed as the file 'HOMER.MOV' on the CD-ROM.

embodies many aspects of potential confusion for the participant: acceleration down an inclined plane; projectile motion; and, an Aristotelian sudden change in motion. The cartoon nature of the probe serves to provide a new, and perhaps less threatening, context for participants to apply their understandings to, and the sequence of related events provides some complexity that may encourage more extensive discussion than if it consisted of only a single event (i.e., only one stage).

Key aspects of stage 1 are:

1. Newton 1 – force and motion (what initiated it and sustained it?).
2. Newton 2 – what forces are acting, where, and for how long?
3. Vectors – acceleration, force, velocity, resolution, normal reaction, momentum.
4. Weight – versus mass, effect of gravity, vector properties.
5. Effects of gravity.

During the 'flat' phase Homer performs an 'Ollie' (Broadt, 1991) — a skateboard jump in which he does not hold on to the board, lands back on the board, and continues the previous projectile motion. The horizontal velocity then diminishes rapidly, and Homer begins to fall slowly, and then suddenly falls almost vertically downwards in an impetus-like[33] fashion (e.g., McCloskey, 1983a, p.114B).

Figure 6-14: The slope.

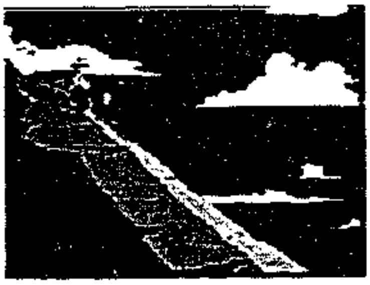


Figure 6-15: Top view.

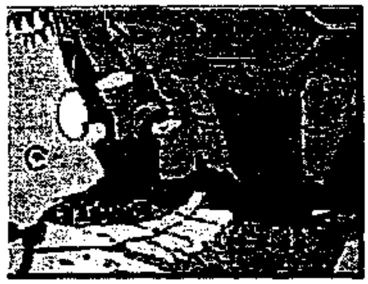


Figure 6-16: Moving.

Figure 6-17: Jump starts.

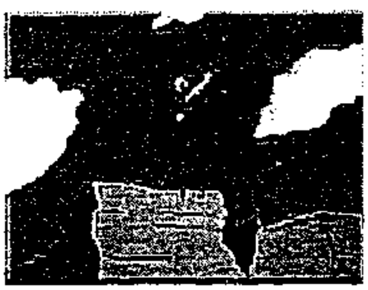


Figure 6-18: Ambiguous path.

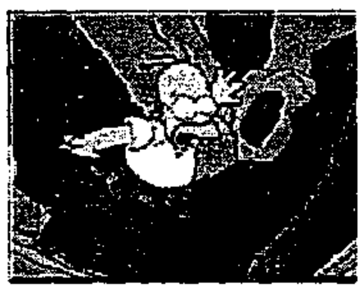


Figure 6-19: Ambiguous path.

Figure 6-20: The Ollie.

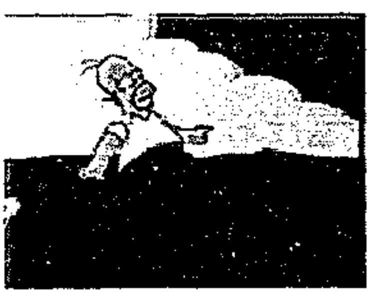


Figure 6-21: The Ollie 2.

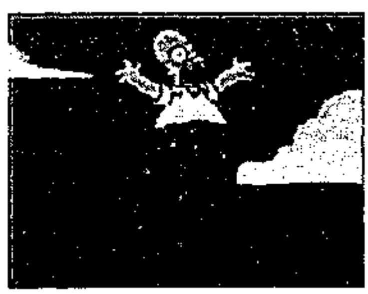


Figure 6-22: Sudden fall.

The projectile motion in this video is inconsistent and ambiguous, appearing to be essentially flat in some scenes, but curved in others (see Figure 6-23 - Figure 6-31). In this regard it contains aspects of FCI probes 16 and 23[34], as well as of McCloskey's (1982; 1981) curvilinear impetus principle when Homer undergoes projectile motion. The whole projectile path provides the opportunity to revisit these issues.

33. i.e., FCI misconceptions taxonomy item 12: loss/recovery of original impetus.

34. Section A.3

The Ollie sequence provides the participants with a common event[35] (the Ollie) occurring in the absence of a supporting surface, and so requires them to be clear about the application of Newton's second and third laws. Potential sources of confusion with the Ollie sequence include:

1. Whether the skateboard would be pushed away or remain in essentially the same relative position.
2. Whether the inertia of the skateboard would be 'sufficient' to allow Homer to exert sufficient force on it to actually make the Ollie.
3. What effect an impulsive (as opposed to constant) force means for (a) the application of Newton's second law in predicting skateboard motion, and (b) for Newton's third law for predicting whether a reaction force could, in fact, allow Homer to make the Ollie.
4. What the significance of both the skateboard and Homer undergoing projectile motion would be on Homer's ability to actually exert a force on the skateboard[36].

This issue is taken up in the case of free-fall in the Road Runner probes. Other physics issues of interest embedded in this probe include:

1. Homer's sudden fall has little resemblance to 'correct' projectile motion, but has a strong resemblance to the motion expected from an impetus-model of motion (see Figure 4-3 on page 91).
2. Whether the point at which the horizontal component of velocity suddenly diminishes is consistent with the participant's model of motion.
3. The nature of the accelerated motion as 'Homer' rolls down the hill — what is its nature and origin; how can it be described?
4. Describing the variable velocity and speed during projectile motion; e.g., what causes the reduction of horizontal velocity during projectile motion?
5. The nature and effect of Force and Gravity in the different stages.

The five stages depicted in Figure 6-13 provide a fruitful context for eliciting the participants' understandings of the relevant physics (cf. Section 4.4), and (arguably) this short sequence of interrelated changing events such as rolling down a slope, projectile motion, the Ollie, and falling within the one probe, presents a more

35. in youth culture.

36. i.e., in comparison to the common 'person in a falling lift' example - which has an obvious solid floor for the person to exert a force on.

complex cognitive challenge than those in the FCI, where such events are decoupled into individual questions. The linking of consecutive events is a key aspect of this, and subsequent, video probes. The opportunity to provide the participants with both new and linked contexts for exploring their understandings of physics was, apart from their significance in the origin of this thesis[37], a major factor in their inclusion in the research protocol for this thesis.

6.4.3.3 THE ROAD RUNNER VIDEO PROBES

This series of probes further develops some aspects of the Simpson's probe - acceleration on an incline, projectile motion, falling, as well as introducing inertial, elastic, and rotational events.

6.4.3.3 (a) Road Runner video clip 1

There are three aspects of this video sequence; the initial acceleration of the character down the slope, the subsequent projectile motion across the gorge, and the terminal impact.

6.4.3.3 a.(1) Sequence 1.1 – Initial motion

This video-clip (Figure 6-23) is similar to phase 1 of the Simpson's video-clip. It commences with the cartoon character 'Wylie Coyote' on skis, perched on top of a mountain – similar to Homer's initial state, but in this case an elastic deformation occurs, resulting in a lengthening of his body as the feet move down the slope. His

37. See page 19.

head moves last, following an extreme elastic deformation of the body before the body returns to its normal shape, and the chase continues.

Figure 6-23: Probe 1.1 Elastic deformation in response to fall commencing.

This 'elastic' scenario is common in cartoons, and is displayed in many situations where free-fall is about to commence. This scenario is challenging to students because it can be confused with classroom observations of the slinky-springs', that appear to move in this fashion. This potential confusion between the motion of 'slinky springs' (KCTA TV, 1994) and essentially rigid vertebrate animals could possibly be due to the limited use of examples involving non-rigid bodies (Newburgh & Andes, 1995) in many introductory physics texts and courses. Arguably, students could perhaps conceive that the exaggerated deformation in the cartoon is a parody of an event that might be too small for them to notice in real life.

In deciding to use this probe, I had considered the possibility that the participants might make links with their comments on the Simpson's probe, as the two initial scenarios are similar in terms the characters sliding down a steep, natural, incline, and then undergoing projectile motion. This should have facilitated the development of the questions about the reality of this scenario by providing a 'compare and contrast' situation. Some of the major physics issues that I anticipated that the participants might respond with are similar to those identified by Watts

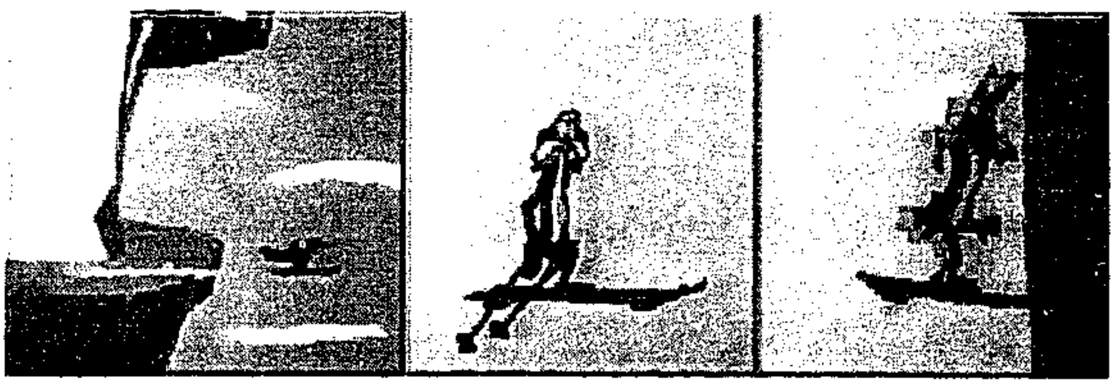
(1982; 1981) in school children (see page 116):

- Differential gravity: the variation of gravity with altitude could be responsible for variable forces acting on the body.
- Selective gravity: it does not act on all things in the same way at all times.
- Differential action: gravity begins to operate when objects start to fall down, and continues until they are at rest on the ground - perhaps explaining why the feet accelerate the most by being the first part of the body acted on by gravity.

6.4.3.3 a.(2) Sequence 1.2 – Projectile motion

In this clip (Figure 6-24), Wylie runs off the cliff at high speed, and then maintains an almost linear motion across the gorge before hitting the wall on the far side.

Figure 6-24: Wylie's projectile motion phase.



In the collision the skis are impaled on the cliff face. His feet stop instantly with the skis, and his body remains rigid, vibrating from the apparent effects of the collision, without any evidence of his bodies inertial motion continuing when the ski stops. This provides a context for probing Newton's laws. The probe is similar to the projectile phase of the Simpson's probe, but differs in the lack of conspicuous falling motion in the projectile phase, and the nature of the terminal stage.

6.4.3.3 (b) Road Runner video clip 2

This clip introduces two new issues — whether a falling body can create a rotational torque on itself, and if, and how, the kinetic energy resulting from free-fall can be stored and used to do work on a falling body as it impacts on the ground. The terminal elastic collision is a different context for probing understanding of Newton's laws.

Figure 6-25: Falling starts.

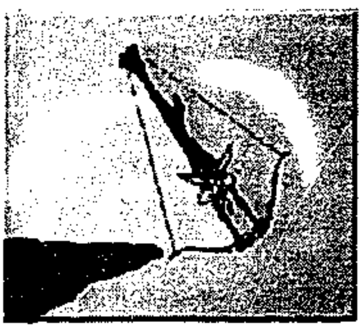


Figure 6-26: Falling.

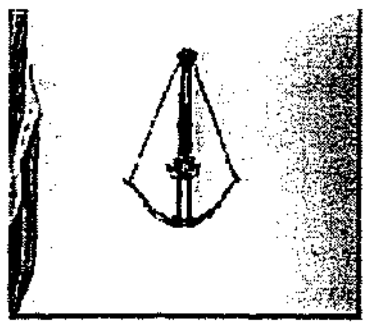


Figure 6-27: Rotating.

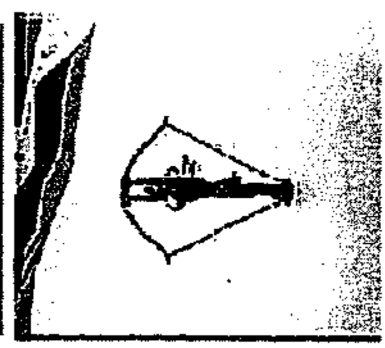


Figure 6-28: 180° rotation.

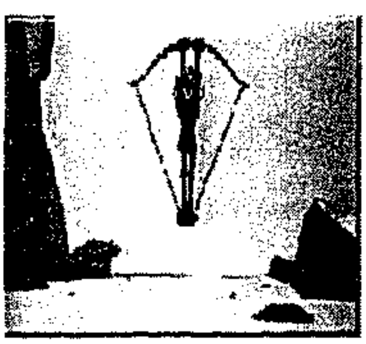


Figure 6-29: Compression.

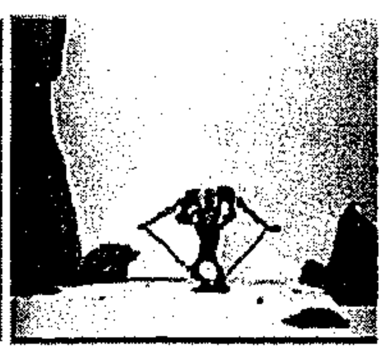
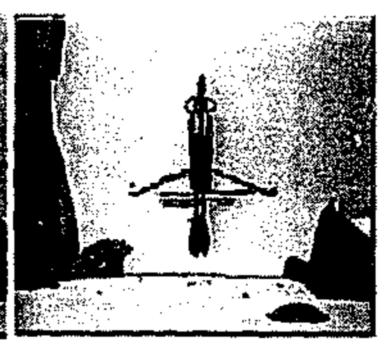


Figure 6-30: Rebound.



The cause of rotation during falling is ambiguous in the video, but it can be regarded as either a continuation of the rotational motion that caused the initial fall over the cliff (Figure 6-25), or as the result of some torque created in falling, either internally, or from differential air resistance (as in 'air surfing'[38]). For example, participant Alan:

38. using the limbs to guide the direction of motion in the free fall of a person from an aircraft.

Alan: You know he's falling vertically, his head was down wasn't it? And he's falling consistently, not turning at all ... unless he does something like the sky divers do to move their hands in a certain way to make the air currents turn his body around, he couldn't have done that.

The rebound phase also provides a useful context for exploring understandings of force, momentum and energy in the context of collisions. Helen[39], for example, while predicting a reasonable answer in regard to the bow causing a rebound, does not actually address the nature of the collision itself, nor the quantities involved:

Helen: Because he is accelerating towards the ground, and he would have to immediately ...um slow himself right down completely even though he's travelling quite fast into the ground. And still have the energy stored in the bow from having it stretched out, Then when he hits the ground, he as to keep his body rigid so that he can, so that the energy is still in the bow, and then hold the bow in one position while he hits the ground.

Jim[40], however, apparently struggles to find appropriate language to explain the rotation, falling back onto animistic terms rather than Newtonian constructs such as torque and angular acceleration:

Jim: The dive - going down, there was a sort of 'cat-like' force that turned him onto his feet, ...
Int: Why? What would need to happen...?
Jim: Maybe um ... more weight in his feet to pull that down quicker compared to...
Int: So you think the weight in the feet would help stabilise that?
Jim: Yes.

Jim however fully appreciates the cartoon nature of the probe, and it is possible that his language has been framed with that in mind — i.e., using a cartoon language genre rather than a formal physics representation:

Int: What about when he landed and went flying up. Any thoughts on that?
Jim: Well, it's just a cartoon!

39. one of the study participants.
40. one of the study participants.

6.4.3.3 (c) Road Runner video clip 3

This clip (Figure 6-31 - Figure 6-33) presents the common cartoon scenario of bodies falling selectively after some supporting structure has been removed. The clip provides a context to re-examine the selective nature of gravity (similar to Figure 6-23), and the understanding of inertia and force in a different context to those used previously.

Figure 6-31: Floating

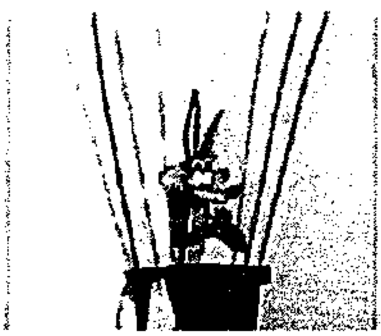


Figure 6-32: Stationary

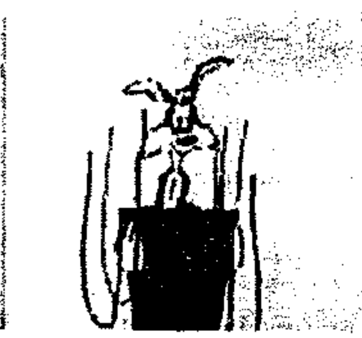
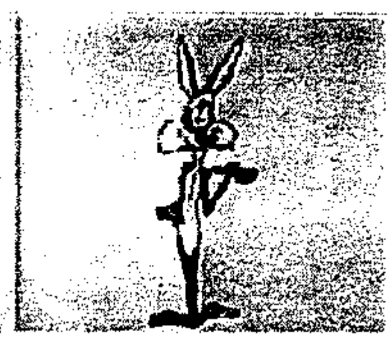


Figure 6-33: Gondola falls.



The clip, like the following one, is an extreme example of Haye's idea of suspending reality, as with most of these clips, the events depicted appear to be so far from reality as to defy belief. However, it was felt necessary to include such extreme examples in order to test the extent of the participants' beliefs and understandings. Arguably, some of the events depicted in the other clips might be believed because they could be perceived as occurring too rapidly to be detected without the benefit of slow-motion replays.

6.4.3.3 (d) Road Runner video clip 4

This clip (Figure 6-34 - Figure 6-36) further examines aspects of inertia raised in the previous clip, and provides a context to examine understandings of the effect (if any) of mass, and size on free-fall, as well as reasons for the differential acceleration observed in the clip.

Figure 6-34: Stationary.

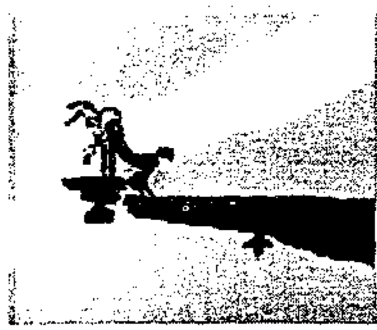


Figure 6-35: Falling.

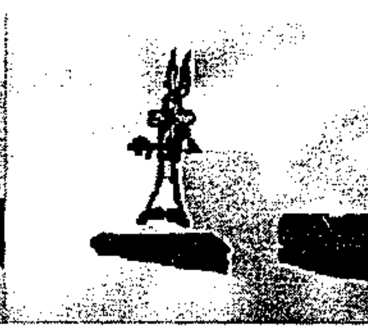
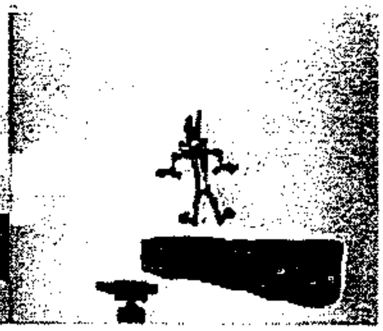


Figure 6-36: Differential acceleration.



6.4.4 *Gravitation™ planetary probes*

This series of probes models simple single-planet environments such as might be discussed in Unit four of the VCE physics course, others which involve the interaction of 'asteroids' with a planetary couple, and some that consist of complex multi-particle examples. The environments serve as sources of discrepant events to help to elicit the participants' understandings by requiring the participants to give detailed and precise responses to very specific gravitational events. The probes form a progression from single-planet systems, through dual-planet systems, to multi-body systems consisting of a planet and many asteroids. This sequence has been developed in accordance with the desire to collect fine-grained data about their content knowledge and T-PCK.

Many of these probes are based around orbiting asteroids or their capture (or near capture) by planets. Newton considered such gravitational capture to be mathematically impossible, but later models by Alexeyev, Schmidt, and Sitnikov (see Osipov, 1992) suggested that partial capture was possible. The capture of comet

Kwerns-Kwee by the planet Jupiter confirmed the reality of gravitational capture (Osipov, 1992). There is therefore a sound scientific basis for including it as a feature in this series (cf. Tancredi et al., 1990), as well as its relationship to the context of Near Earth Asteroids as discussed in Section 2.5.2 (cf. Hahn, 1992). However, it is not expected that the participants will be familiar with the relevant theory, because the mathematics underpinning it is far too complex to be relevant at this level. Rather, capture is used here almost phenomenologically — it just happens, as a focus for discussions about the nature of the gravitational fields that might be responsible for such motion. These probes do not necessarily purport to be realistic[41], but rather are a context for discussion and exploration. In this sense, there is some duplicity involved, as the participants are required to explain their observations and thinking in terms suitable for the VCE, when such explanations are presumably incapable of providing the correct mathematical answer. However, as the focus of the research is in eliciting their knowledge and ideas through their discourse, the use of such probes provides a rich source of data, and are used in accordance with Erickson's (1999) notion of pragmatic research designs (cf. Hirst, 1971), and Hayes (1979, p.267)[42] argument that '... it is important ... to find a "normal" world (simulation or model) in which the REAL "normal" world rules could be suspended....so that it seemed reasonable to ask if such rules DID apply.'

41. other than by providing a fairly realistic appearance on screen.

42. as previously quoted on page 151.

6.4.4.1 FOCUS OF THE PROBES

These probes are designed to explore the participants' understandings of orbital motion from several perspectives:

1. Satellite capture.
2. Gravitational deflection - the 'slingshot' effect.
3. Multi-particle interactions.

A key feature of each probe is the existence of a radial gravitational field surrounding each particle (planet or satellite) in the simulation. There is no explicit indication of its presence (other than the presence of the mass itself). As discussed above, not all of these probes are intended to be authentic simulations of planetary events. However, probes 1-3 are realistic simulations of a planet-asteroid interaction. Probes 4-6 involve the interaction of an asteroid with a hypothetical binary planetary system. Probes 7-10 explore the interactions of a set of asteroids that suddenly appear (all with the *same velocity*) near various hypothetical planetary systems[43]. These provide the tools for repeated probing of planetary gravity concepts, Kepler's laws, field concepts, and Newtonian concepts through the use of ten graded computer microworlds.

A key issue in this series of probes is how well the participants understand the nature of the gravitational field surrounding each mass, and how that field can affect other masses (and also be affected by them). Central to this is their ability to understand the principle of Superposition (for estimating resultant gravitational field directions) and to intuitively apply the Newton's inverse square law of gravity to the interactions that occur. The multi-particle probes, particularly probe-7, also

43. Probe 7 is the closest to any natural situation.

examines their understandings of Kepler's and Newton's laws because when the asteroids suddenly appear, all with the same velocity at the same time, but in different positions along the (presumed) orbit, they are on slightly different orbits (as a consequence of their different positions and same velocity at the same time). Other than with probe-7, the multi particle probes explore complex, and quite unrealistic, contexts. The rationale for their inclusion is both that of Hayes[44] (1979), and the fact that they produce striking visual images that require the participants to provide an extended response as to their possible origins.

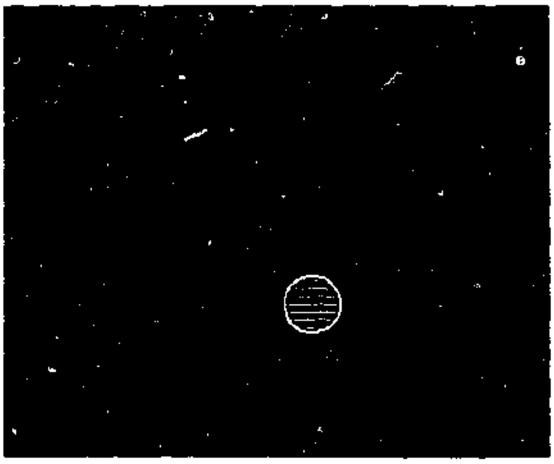
6.4.4.2 Probe details

This section provides specific details of the nature and use of each probe in this series. The first diagram in this section (Figure 6-37) is a portion of an actual screen display from the first probe. Subsequent images (up to Figure 6-50) in this section will depict the features of the probe rather than the actual display in order to make explicit the design features of each probe.

44. as above.

6.4.4.2 (a) Planetary world 1

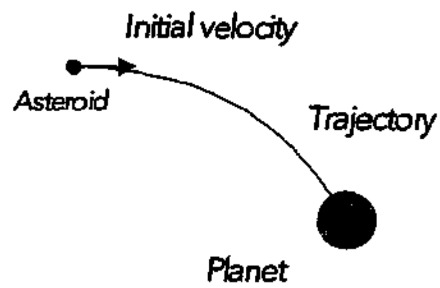
Figure 6-37: Probe G1 – single planet probe 1 bypass scenario.



This environment consists of a planet (fixed at the centre of the screen) with an 'asteroid' which is passing from left to right (from the top left-hand corner) through the gravitational field around the planet. There are no visual clues provided about the field direction or strength, nor of the speed of the asteroid. The initial path takes the asteroid past the planet at high speed, with a mild deflection due to gravitational attraction. The participants are asked to predict what will happen when the asteroid passes the planet, and what causes the observed motion. They are then shown how to manipulate the asteroid's velocity, and asked to explore a number of different velocities, and to comment further on what was observed, and the origins of the motion.

6.4.4.2 (b) Planetary world 2

Figure 6-38: Probe G2 – single planet probe 2 impact scenario.



This probe is similar to the previous one, except that the asteroid, moving at low speed, collides with the planet. The participants' are again required to explain the observations, and to vary the asteroid's velocity in order to explore their understandings what causes the collision, rather than to pass by. Where possible, they were asked to explore the 'boundary' conditions which make the asteroid either collide with the planet or avoid it. Creating the boundary conditions with the software during the interview, however, is an iterative, often hit-or-miss, process and can take considerable time to determine. Most participants were not able to determine any such conditions in the time available.

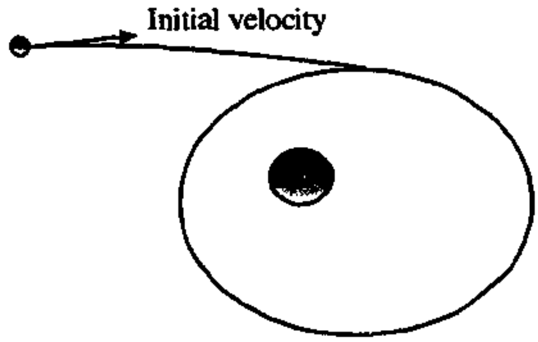
6.4.4.2 (c) Planetary world 3

As an extension of the previous two probes, in this probe the asteroid is captured into orbit. The participants are asked to vary velocity and mass (if desired) to determine the boundary conditions[45] under which capture can occur (as in the previous probe). Capture is quite difficult to achieve by trial and error, as it requires the exact combination of velocity, mass (of both planet and asteroid), and initial displacement from the planet. The purpose of this probe was to explore both

45. cf comments on boundary conditions in Section 6.4.4.2 (a).

Newton's law of universal gravitation (Section 4.3.2), and Kepler's laws of planetary motion (Section 4.3.2.1).

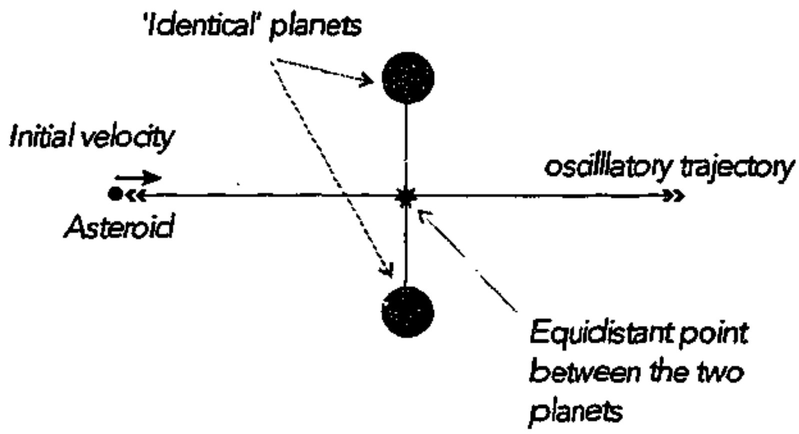
Figure 6-39: Probe G3 – Orbital capture scenario.



6.4.4.2 (d) Planetary world 4

This (Figure 6-40) is the first of a series of multi-particle probes[46] that focus on the participants' knowledge of gravitational fields, gravitational force in 'non-traditional' contexts[47] (cf. Bliss, 1989, p.267). This, and the following two probes, examine the interaction of an asteroid with two identical planets.

Figure 6-40: Probe G4 – Horizontal oscillator scenario.



46. see Table 5-2 on page 152.
47. i.e., single-planet contexts such as those used in probes 1-3 in this section.

The principal feature of this probe is that the asteroid moves along a horizontal axis of symmetry[48] between the two planets where the vertical components[49] of the gravitational force on it (from each planet) are cancelled out. The resulting motion of the asteroid is that of a simple harmonic oscillator. This is used to elicit participants' understandings of vectors in the context of both force and field, and the nature of the gravitational field around the planetary couple. For the purposes of this probe, the asteroid is assumed, as a first-order approximation, to have no effect on the field. In this case, this approximation can be justified on the basis of the small mass of the asteroid in comparison to that of the planets.

Participants are asked to explain the nature of the gravitational field represented here, and its cause. They also are required to describe the motion and its origin, and to compare and contrast it to the previous three single-planet probes. In doing so it was anticipated that they would be able to use vector representations to explain their answers.

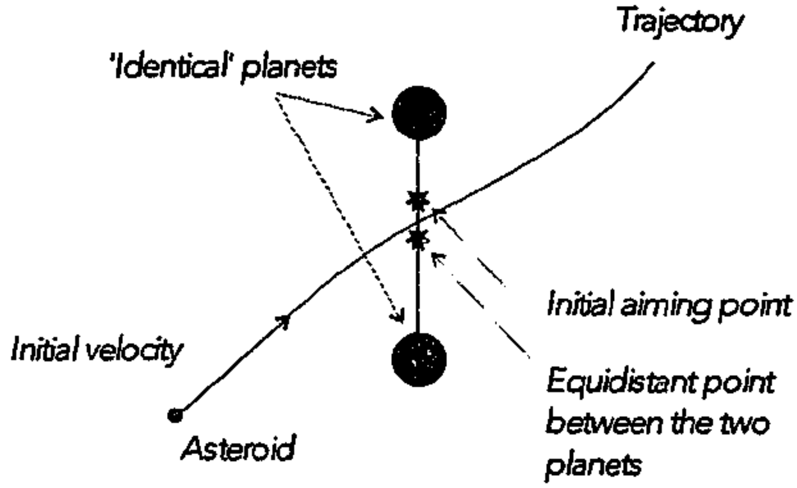
6.4.4.2 (e) Planetary world 5

This probe (Figure 6-41) differs from the previous one in that the asteroid passes 'off-axis' through the equidistant-point between the two planets. In this case the forces on the asteroid from each planet differ at every point except the equidistant point.

48. i.e., reflection.

49. as represented in the diagram and on screen in the actual probe.

Figure 6-41: Probe G5 – high speed pass between planets.

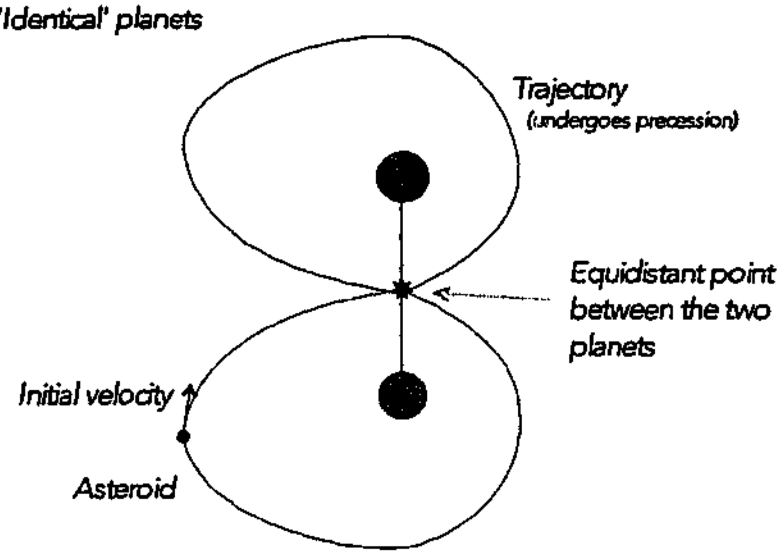


Participants are expected to be able to describe this in vector terms, and to discuss the differences from the previous probe. It was anticipated that this probe would raise issues about the inverse-square law, with the effect of distance being most evident around the vicinity of the equi-distant point as the path changes at an inflection point.

6.4.4.2 (f) Planetary world 6

This probe develops issues raised in the previous probe by presenting a pre-designed scenario in which the asteroid is positioned so as to pass along an orbit about both planets as in Figure 6-42. This is a more complex orbital scenario than that employed in probe 3 above, and provides the opportunity to revisit issues about the understanding of the nature of the gravitational field around the planets, the forces acting on the asteroid, and the vector nature of these quantities.

Figure 6-42: Double-planet orbit scenario showing final orbit.



6.4.4.2 (g) Planetary world 7

This probe (Figure 6-43) is the first in the series of multi-asteroid scenarios. These focus on exploring the participants' understandings of radial gravitational fields, and the effect of mass, velocity, and displacement (from other objects in the simulation) on orbital motion. The mass of the central planet, and hence the gravitational field strength, is not kept constant in these multi-particle probes, but has been varied on a probe-by-probe basis in order to epitomize the various graphic displays. The key feature of the design of all of the multi-asteroid scenarios is that the asteroids suddenly appear in the space, all with *identical* mass and velocity, and at different positions on a straight line. This last point is significant, because it means that they are not going to follow the same single orbit. For example, in Figure 6-43 the asteroids 'appear' in the scenario all moving horizontally to the left with the same velocity. The participants might interpret this as if it were a time-lapse photograph in which the same particle is shown at different *times*, and thus misunderstand that each is on a slightly different orbit by virtue of its different displacement but same the velocity at the same initial instant[50] (see Figure A-21 on page 32). Additionally there are the asteroid-asteroid interactions to consider because they are in close proximity in this, and the following probes in this section, causing a small perturbation in their paths as in Figure 6-44[51].

Figure 6-43: Probe G7 –Multi-particle probe 1 initial conditions.

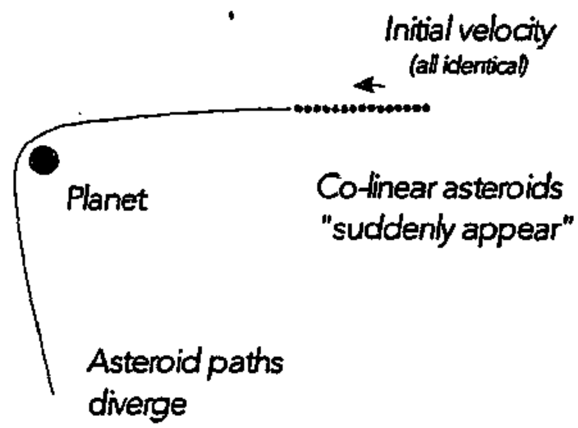


Figure 6-44: Perturbation to orbit before, and fan-out after, passing the planet.

It was anticipated that two of the possible arguments that the participants might present would be in terms of either:

50. as opposed to the time-lapse photograph which is the same particle on a single path.
51. i.e., the path that they would follow if only (any) one of the asteroids was present.

(a) an extreme case scenario where two asteroids of identical mass *and* velocity, one close to the Earth, and the other near (say) Pluto appear simultaneously *on the same path* at that instant (cf. \Figure A-21). They would follow different orbits because of the effects of the different initial forces and acceleration[52];

(b) using a vector representation that showed that the gravitational force (magnitude and direction) on each was slightly different at the moment they appeared, thus creating a different initial speed and direction.

In this probe, this issue is most significant as the gravitationally-induced acceleration around the planet visually 'fans out' the paths because of the differential effect of gravity on each asteroid in each different orbit[53]. This forms the focus of the questioning about this probe. Participants responses were generally couched in the same terms as for G1-G3, but had difficulty in articulating reasons for the different asteroid paths, for example, participant Jim:

Jim: They were attracted again to the planet which makes the asteroid course move around it. As each asteroids going towards the planet, it speeds up and the force between the asteroids… Ah. Um… How can I explain this? There is a force attracting the asteroids to one another. And then…

Int: Between each other. You mean between those individual pairs of asteroids?

Jim: Yeah. And then, when they get closer to the planet, they… the gravitational pull of the planet forces them to leave their course and … curve around.

Int: Why do they spread out as they go around there?

Jim: Cause the distance… the um ah force of it from the planet is pulling the asteroid quicker.

6.4.4.2 (h) Planetary world 8

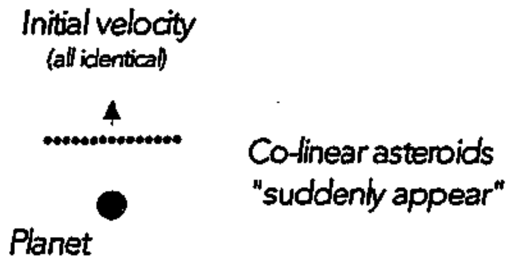
This probe is similar to G7, but differs from it in that the asteroids all move away from the planet in the manner depicted in Figure 6-45. The Newtonian prediction

52. Abelson, diSessa, & Rudolph's (1974) velocity-space model can also be used to demonstrate this.

53. similar in *visual effect* to the way in which magnetic fields are used to split the paths of particles of different mass and charge in mass-spectrometers.

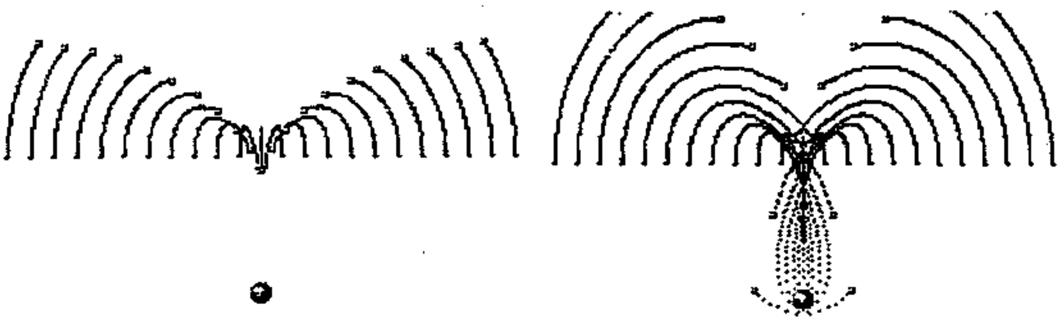
(arguing on the basis of the inverse-square law) would be that the gravitational force is greatest closest to the planet, and weakest furthest away, therefore affecting the central asteroids most. The predicted motion therefore might be that the central asteroids lag (unevenly) behind the others, or perhaps even that depicted, in which the gravitational force eventually reverses their motion and attracts them to, or around the planet. It is unlikely that participants would envisage the complex motion shown in Figure 6-46.

Figure 6-45: Probe G8 – Multi-particle probe 2 initial conditions.



Because of the particular symmetry employed in the setup, the resulting motion appears to be far more complex than in the previous probes. The differential effect of gravity here arises (Figure 6-46), as in the previous probe, from the differing distances of the asteroids from the planet. In this probe, the effect of distance is far more pronounced than it was in the previous one. In Figure 6-46, at T=650, the 16 asteroids furthest from the planet have not yet returned to the line defining their initial position, whereas others have passed by the planet. This variation is intended to raise the effect of distance with participants, or develop aspects raised in the previous probe.

Figure 6-46: Probe G8- asteroid motion at t=75 (left) and t=150 (right).



6.4.4.2 (i) Planetary world 9

This probe is similar to the probes G1-G3 (except that it has more 'asteroids') and G8, except that the asteroids appear as in Figure 6-47, moving vertically upwards. This probe provides a different context with which to continue exploring issues raised in the previous two probes. For the Newtonian student, it presents another simple example of the application of Newton's law of gravitational attraction to predict curvature around the planet and possible resulting orbital motion.

Figure 6-47: Probe G9 – Multi-particle probe 3 initial conditions.

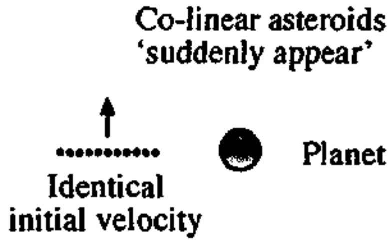


Figure 6-48 shows the asteroids' motion at two stages. It was anticipated that the simple orbital motion would be readily predicted, and would offer a 'traditional' context in which to discuss the inverse-square law and its ramifications.

Figure 6-48: Asteroid motion at t=100 (left) and t=800 (right).

Participants, however, generally provided simple descriptive summaries of what might happen without providing a mathematical or scientific argument for the origin of such motion:

Alex: The ones closest to the planet will have a greater… curving effect … I don't know… The planet will …attract them more than the ones further out.

6.4.4.2 (j) Planetary world 10

This probe (Figure 6-49) was designed to show motion that included complex asteroid paths, and both asteroid and planetary collisions, and is, perhaps, the most unrealistic probe of this series. It was anticipated that by having such a complex dynamic environment, many of the issues raised in all nine previous probes could be used by participants in their explanations of these events.

Figure 6-49: Probe G10 – Multi-particle probe 4 initial conditions.

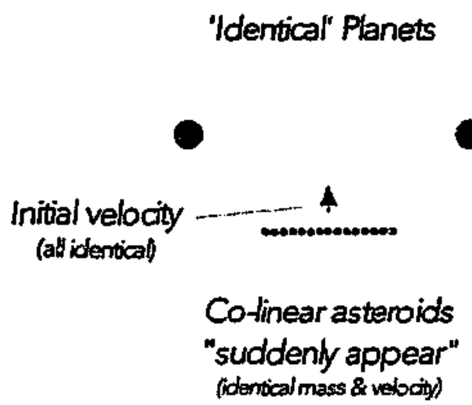
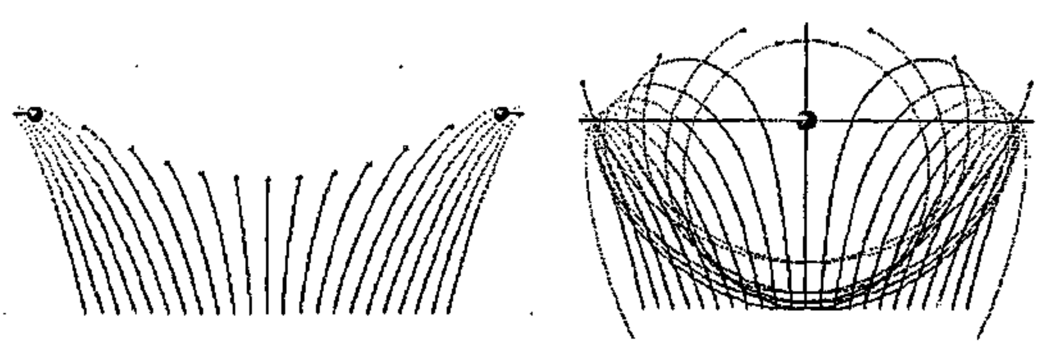


Figure 6-50 shows the resultant motion at two stages. Note that in the right-hand diagram, the two planets have collided to form a single planet that the asteroids finally end up orbiting. This creates a two-stage scenario, with the initial motion towards the two separate planets (as in the left-hand diagram), and the subsequent motion under the influence of the larger single planet (as in the right-hand diagram).

Figure 6-50: Asteroid motion at t=250 (left) and t=650 (right).



As in the previous probes, simplistic descriptions were preferred over formal mathematical or scientific arguments e.g., in the case of participant Steve:

Steve: Ok so I think maybe this half will be attracted towards this planet and the other half to this.
Int: Ok let's have a look.
Steve: Oh they are all hitting! I didn't think they would hit!

6.4.4.3 Vector Worlds

This series of probes is used to refocus the participants' thinking on the vector nature of the Newtonian model that they had discussed (implicitly) in the preceding video-probes and computer-based probes. These probes are placed at the end of the sequence so as to be able to draw on the subjects' prior experiences in the interview, and therefore perhaps help them to draw together their ideas. Also, for those subjects with poorly developed Newtonian understandings, being confronted with a series of Newtonian representations could act as powerful stimuli with which to make them rethink their previous answers. For those subjects with well developed Newtonian concepts, they could serve to affirm their understandings, and perhaps help them to articulate them further in a more formal and familiar context and format.

Interactive Physics™ (IP) was used to create these probes because it allows rapid phototyping and development of data-driven dynamic simulations, as well as accurate graphical displays of the resulting motion (Knowledge Revolution, 1992). In particular, IP allows the creation of 'fields', including various types of gravitational fields (a key feature in this study). Each object in an IP simulation can contain relevant physical properties such as mass, velocity, acceleration, density etc., and represent these in many different ways. Each of the 'vector worlds' provides explicit visual representations of the vector nature of force, (either of a component, or the total force), acceleration, and velocity, as well as providing visual tracking of the objects' paths. The vectors are evident on screen, and a variety of graphs and tables, can easily be added by the participants, providing them with a choice as to the amount of information they wished to examine in each case.

In accordance with the ramifications of a semi-structured interview situation, some participants did, in fact, work through the sequence of five probes, but others, exploring issues raised in probe one (of this series) simply added more vector representations to it, effectively recreating the sequence. Probe five, however, was used with all participants.

The first four probes in this series examine a single asteroid passing around a planet — a deliberate link to previous probes. The difference between the four probes is that when they are presented to the participants, each displays a different representation of a vector quantity such as velocity, acceleration, or gravitational force. The participants are asked to observe the probes, and to explain the significance of the varying vector quantities as seen by the vector lengths, graphs, or numeric data (depending on which the participant chooses to use). Vector World 1 (Figure 6-51) exemplifies the environment used in the first four probes.

Figure 6-51: Vector probe 1 with gravitational force vectors displayed.

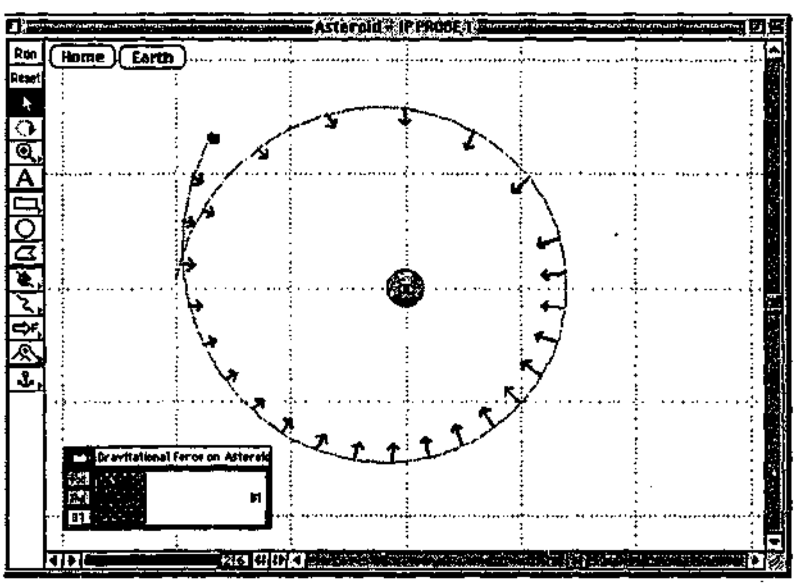
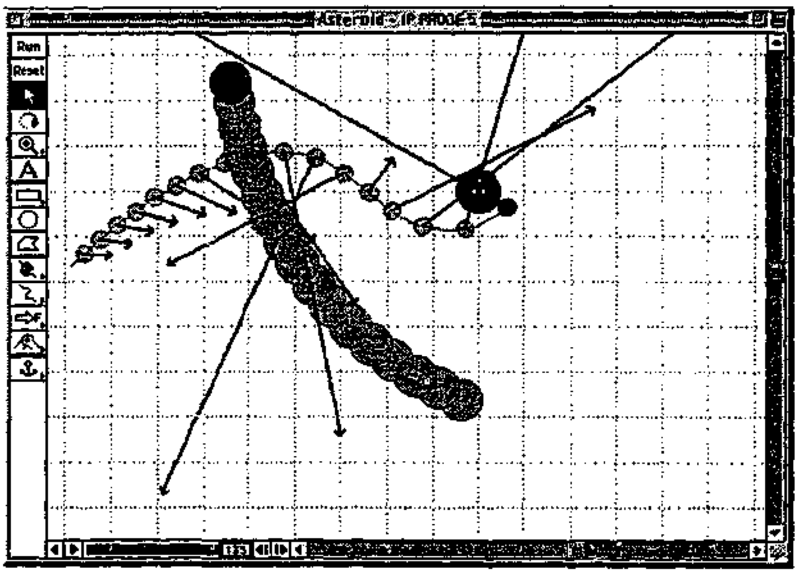


Figure 6-52 shows the last probe in which an asteroid and two moving planets come into close proximity. The vectors shown in this diagram represent the nett force acting on the asteroid. Participants are expected to be able to discuss the nature of the motion in terms of the force vectors that appear as the probe is run.

Figure 6-52: Vector probe 5 showing nett force on the asteroid.



6.5 Chapter Review

This chapter reviewed the nature of the data collection, describing the procedures for collecting both qualitative and quantitative data, and the issue of granularity (and how this was accommodated). The thinking behind the design of the probes was articulated, details of the probes themselves were provided — in which their nature, expected and actual responses, and relevant issues were described. Processes for the analysis of both qualitative and quantitative data were discussed and related to aspects of T-PCK and subject matter knowledge by means of a NUD•IST database.

Chapter 7

Participant Data: Nature and Issues

"Yes, they're all fools, gentlemen. ... But the question remains, 'What kind of fools are they?' "

7

Participant data: nature and issues

7.1 Introduction

This chapter reports on the interview data, presenting a concurrent content analysis that both examines the data for its fit to Newtonian concepts, and attempts to identify the nature of the participants' difficulties, if any, with the relevant physics concepts. The implications of participants' specific difficulties are developed in Chapter 8, where they are considered in the context of the development of a knowledge base for teaching the related physics content (i.e., the 'Gravity' context of the VCE year 12 physics curriculum[1]).

Because of the volume of qualitative data collected, this chapter presents segments of each of the participants' transcripts that illustrate significant aspects of their responses in terms of the semantic content analysis[2] conducted in this chapter, and of issues arising from them[3]. For each, the introductory questions and answers are presented almost verbatim[4], so that the reader can develop a feel for the detailed nature of the responses. Subsequent probes are presented more concisely. This

1. Section A.1 on page 1 of the appendices.
2. see Section 7.1.1 on page 239.
3. The complete transcripts are on the associated CD-ROM.
4. With minor editing to remove extraneous text or 'noise' — according to Lemke's 'lexical' approach to transcription (Lemke, 1998, p.1177).

approach was taken partly because, in Strauss' (1990, p.215) terms, of the need to let the data talk for itself — to provide the reader with an authentic understanding of the content, as opposed to a shallow, summative, understanding. In Erickson's terms (1998, p.1168-9), the participant vignettes (the 'particular description'), along with an 'orienting commentary', provide two essential components of a qualitative research report. The conclusions of this chapter form the third — the 'general description' of the data. This approach to presenting and reporting on the data stems also from Leininger's position on the orthodoxy of quantitative research methods (cf. Section 5.3.2 on page 141):

> … qualitative researchers should not rely on the use of quantitative criteria such as validity and reliability to explain or justify their findings Such reliance reflects a lack of knowledge of the different purposes, goals, and philosophical assumptions of the two paradigms. (Leininger, 1994, p.96)

7.1.1 Data transparency and validation

Part of the research for this thesis was to find an approach to analysis that incorporated Lythcott and Duschls' (1990) concerns about the need to provide defensible claims based on the arguments linking evidence to conclusions by incorporating a conscious effort toward sound argumentation. The layout of this chapter, with data and analysis presented concurrently, is a response to this need (and another research feature of this thesis) by facilitating the reader's ability to both validate and examine both the data and analysis in ways that are not commonly used for qualitative research presentations in science education.

The development of a model for incorporating explicit analytical commentary alongside its source data in this thesis results from this need, and stems from two sources. First, Keil's (1989) use of pre- and post-fix annotation, appeared to offer an efficient and consistent approach to the analysis of semantically structured interview transcripts (cf. Lemke, 1998, p.1180) in a way that rendered them open to inspection and validation by a reader (cf. Lythcott & Duschl, 1990). Second, in a similar way to that in which diSessa uses the term 'reconstructible'(e.g., diSessa & Abelson, 1986; Nicholson, 1994c) in microworld development as meaning that the basis of decision making can be readily inspected[5] or 'reconstructed' in order to validate students' thinking about the context, incorporating analytical comments and coding alongside the source text appeared to offer a similar level of transparency and reconstructability to the research by enhancing the opportunity for validation of the analysis. How this was implemented is described below.

Individual participant's data are presented using a common sequence that is similar to that of the interview sessions (as in Figures 5-2 and 5-3 on page 161), so that evidence of emerging issues or trends in the data, *if and where discernable*, can be interpreted[6] in a similar (presentation) context to that from which it came (cf. Brown, 1976; Strauss, 1990, p.215-6). This also aims to provide insight into the granularity that has been aimed for. In addition to particular annotations — '...an interweaving of discursive propositions' (Strauss, 1990, p.217), or in Erickson's (1998, p.1169) terms, 'an orienting commentary', analytical comments have been placed beside blocks of the text (in a two-column format) in order to raise or emphasise particular issues, posit tentative hypotheses, or to relate the text to other passages, data, or other items in this chapter or elsewhere in the thesis. Such

5. i.e., in the code base for the microworld.

6. in accordance with Erickson's (1998, p.1168) requirements for the inclusion of 'the particular description'.

comments are differentiated from the rest of the text by the use of a sans-serif type face. The use of these annotations is an attempt to develop a coherent semantic content analysis (cf. Lemke, 1983; 1990; 1995; 1998, p.1180) based around Newtonian mechanics. This is facilitated by having data which is structured according to the structure (content and sequence) employed in the semi-structured interviews. This means that the referent texts (for subject matter knowledge) are those of Newtonian mechanics, and do not have to be generated from the data as is the case with, say, grounded theory methods (cf. Cannon, 1998; Glaser & Strauss, 1967; Holsti, 1969).

7.1.1.1 The PCK data

In Section 5.8.2 on page 173, an approach to analysing the participants' PCK was discussed. However, the data reveals little evidence of PCK-like descriptions that are not predicated on erroneous subject matter knowledge. Even then, it's categorisation as PCK is problematic (see Section 7.5.2 on page 354). Such cases are discussed in Chapter 8 as part of the development of a knowledge base for teaching the related physics subject matter.

In the absence of a substantive section on PCK analysis, the content analysis in this chapter forms the major component of the formal 'analysis' of the data (for scientific content matter knowledge) — being supplemented by the FCI data. This chapter, therefore, serves to both present and interpret the data concurrently, serving the purposes of what might otherwise have occupied two separate chapters.

7.1.2 Nature of the annotations

In order to maximise consistency and facilitate comparisons within and between participants, the participants' text is also annotated, where appropriate, according to a scheme *similar* in nature to Keil's (1989, p.70) sufficient/defining notation, in which the use of positive and negative prefixes and postfixes indicate whether a response is 'sufficient' (i.e, it is an adequate answer to a question), or definitive (or not), as in Table 7-1.

Table 7-1: Basis of response categorisation as being sufficient or definitive. (adapted from Keil, 1989, p.70)

Category	Tag	Criteria
Sufficient	s+	An appropriate response that contains or describes characteristic features of the entity.
	s-	Either an inappropriate or erroneous response, or one without characteristic features.
Definitive	d+	An appropriate response that contains a defining feature of the entity.
	d-	Either a response that incorrectly describes defining features, or is devoid of them.

In this thesis, the conventions in Table 7-1 are used to provide a general categorisation of the participants' responses as being sufficient (or not), and definitive (or not). Keil (1989, p.70) notes that there is no algorithm to determine sufficient or defining attributes, but rather, that they are evident from their description. In this thesis, this implies that a competent 'Newtonian' reader should be able to determine the existence or absence of such attributes — as is done in this chapter — by relating the participants' responses to Newtonian theory.

It is important to note that the use of these tags (s/d) is *solely* in order to provide a consistent way of keeping track of responses at *a more general level* than that which focuses on the explicit details of the participants' subject matter knowledge — i.e., they act as 'meta-tags' which provide the reader with an overview of the general nature of the responses. The detailed nature of the embedded subject matter knowledge (which forms the basis of the s/d tagging) may be inspected by examining the content tagging protocol as described below.

For the purposes of this thesis, I have adapted Keil's model to include the presence or absence of a desired content knowledge attribute, which, in this thesis, are related to understanding Newtonian mechanics in the contexts presented in the probes. Table 7-2 lists the basis of this notation model.

Table 7-2: Use of prefix and postfix notation for physics content analysis. (X' may be a concept, law, rule, or argument.)

Notation	Meaning
+X	Correct use/presence of X[a]
-X	Incorrect use/absence of X
X0	No discernable use of standard forms[b]
+X/+Y	Correct use of X implies correct use of Y
+X/-Y	Correct use of X implies incorrect use of Y
-X/+Y	Incorrect use of X implies correct use of Y
-X/-Y	Incorrect use of X implies incorrect use of Y

a. even though it may be the incorrect argument for the particular case under consideration.
b. i.e., as defined by the use of the particular categories adopted for the analysis.

Specific subject matter responses are tagged in this way. For example, using the 'N1-N4' notation (see Section 4.3.3 on page 111) — for example, a passage correctly describing the application of Newton's second law would be annotated +N2, and one with incorrect usage as -N2. Similarly, a passage on projectile motion such as 'the further it gets, it's horizontal speed will decrease due to air resistance' (cf. Section 7.2.7.2 (b)), would be tagged as +5F1 (effect of air resistance). In the absence of further commentary on the projectile's vertical motion, it could also be tagged -5G3 (parabolic trajectory) because that is an essential aspect of a satisfactory explanation of projectile motion.

The use of common 'historical' models (Section 4.2) are likewise annotated using the notations listed in Section 4.2.2.4 on page 95, and Section 4.2.3.2 on page 102. For example, +A3 would indicate a 'correctly argued[7]' explanation using Aristotle's principle of 'greater effort - greater speed'. However, since this is incorrect in Newtonian terms, it *may* also be accompanied by -N2[8], written as +A3/-N2, depending on the context of use. -A3 alone, however, would indicate the incorrect usage of A3. NΘ indicates the absence of Newtonian argument. Likewise, KΘ indicates the absence of use of Kepler's laws. To avoid confusion between the FCI categories, and the related FCI misconceptions categories, specific items from the former will be annotated (FCI) and the latter as (FCIM). When identified in the data, other identifiable misconceptions (such as those in Section 4.4) are cited normally[9] in APA style, e.g., (Nelson, 1991).

It is important to note that these tags are used within a particular transcript; in their development there was no intention to compare their frequency of occurrence across participants because the semi-structured nature of the interviews implies that there will be significant differences between the participants' commentaries.

7. i.e., the student has correctly (faithfully) argued A3 *according to the Aristotelian model.*

8. In this hypothetical example, the student is arguing (incorrectly) about the second law.

9. They can be found in the list of references for this thesis, commencing on page 1.

7.2 Individual participant data

As outlined above, this section presents a series of vignettes of the participants' responses to the interview probes in order to develop an authentic sense of the issues, and a sense of the granularity aimed for in this study. In reading the following responses, it is important to remember that the correct Newtonian response to each probe is, *in all cases*, simple and obvious[10] to a 'Newtonian' student[11] — each answer would probably require no more than one or two sentences, with the exception of the 'planetary probes' which would presumably require more. diSessa's comments about the difficulties that students have when confronted with qualitative problems[12] (diSessa, 1993b, p1) are also important here, because, in this chapter, the focus is on understanding their origin, and how they relate to the participants' ability to explain the context in Newtonian terms.

In order to provide some tentative overall guidance to the reader of this section, Figure 7-1 presents a graphical overview, in the form of a mapping of the relationships between the participants, as determined by their FCI-deduced misconceptions. In Figure 7-1, the different areas of the self-organising map[13] form a two dimensional representation of the differences between participants' FCI-deduced misconceptions as calculated by the SOM algorithm[14] (Honkela et al., 2000; Kohonen et al., 1998). For the purposes of this chapter, the map can be

10. cf. Hestenes and Hellers' (1995b, p.503) claim that in the FCI, the correct responses are so obvious and unproblematic to Newtonian thinkers that false negative responses can only be attributed to carelessness or inattention.

11. i.e., one who completely understands the Newtonian models of mechanics and gravity.

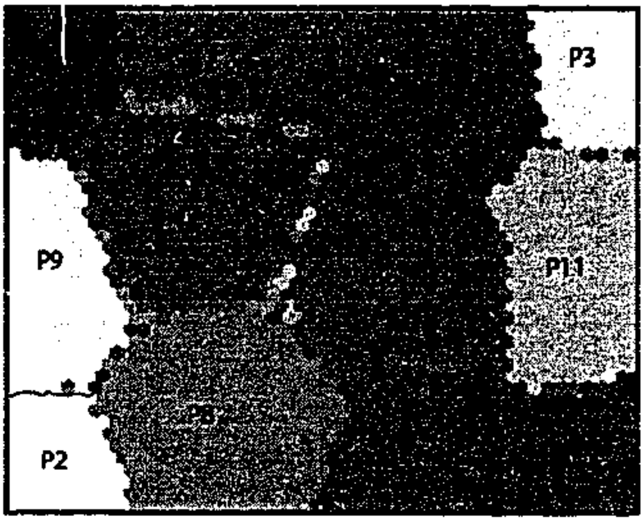
12. At the introduction to Chapter 2.

13. as produced by Viscovery (Eudaptics, 2000).

14. Which used the FCI-generated scores for deduced misconceptions as input — with each category being aggregated.

interpreted as showing *loosely*, how closely particular participants hold similar misconceptions — the distance apart of any two zones is statistically related to their difference in scores. In this particular map, better (i.e., more Newtonian) scores are to be found on the right hand side of the map[15].

Figure 7-1: Self-organising-map generated relationship between participants as deduced from their FCI-predicted misconceptions ('test' refers to no misconceptions being detected).



7.2.1 Joanna

Joanna is undertaking a double-major[16] Mathematics sequence in conjunction with a sub-major[17] study in Physics. Joanna's self-assessment of her knowledge of Physics (in general), and of Mechanics in particular, were both 'average to good'. Her other tertiary science study is a two-year sequence in Earth Sciences. Her physics background is considered to be normal, with three years of tertiary studies in Physics successfully completed (Table A-2 on page 3).

15. nb. the small number of subjects has led to a 'coarse' depiction: lager data sets result in finer detail in a map.
16. Section 2.6.1 on page 40.
17. Section 2.6.1 on page 40.

7.2.1.1 FCI questions

The FCI data (Table 7-3) indicates that Joanna has a moderate understanding[18] of the NFC, with apparently good understandings of the First Law (N1) and superposition (Category 4), but has significant weaknesses in the other categories, including those relating to Gravity[19] (Table 7-4). This suggests that she may have great difficulty in developing Newtonian explanations for the events contained in the probes. In particular, her weaknesses with N2 and N3, which provide the essential foundations for most of the probes, may lead to the use of Aristotelian or Galilean models (Section 4.2), e.g., impetus models, or other erroneous ideas such as those raised in Section 4.4 when discussing the effects of forces on bodies (in terms of N2 and N3).

Joanna's FCI-*predicted*[20] misconceptions (Table 7-5) are *likely* misconceptions, '...loosely related, sometimes inconsistent' (Hestenes & Halloun, 1995b, p.503), that she may hold. These concern impetus (I1, I3, I4), 'active force' (AF1, AF2, AF6), and action-reaction pairs (AR1, AR2), suggesting that (in conjunction with her poor understanding of N2 and N3) she may have great difficulty in correctly explaining the 'planetary' probes, in particular where the effects of varying mass may be misunderstood, and where 'agency' might be confused with either mass or speed. The incorrect response to G3 (heavier objects fall faster) may be related to these, although Hestenes and Halloun caution that the odd incorrect response is not necessarily indicative unless supported by *further* incorrect in-category responses.

18. The FCI only measures the disparity between student concepts and the NFC, not student concepts per se.
19. This is in contradiction to her self-assessment of mechanics knowledge.
20. See Table 6-7 on page 190.

Table 7-3: Joanna - FCI results by category.

FCI category	0 K	1 N1	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	3	7	1	1	4	6	52%
Percentage	50%	88%	25%	25%	100%	38%	

Table 7-4: Joanna - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	3	0	1
Percentage	50%	0%	50%

Table 7-5: Joanna - predicted misconception areas[a] (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	K1	K2	K3				
	×	×	×				
1. Impetus	I1	I2	I3	I4	I5		
	✓•	×	✓•	✓•	×		
2. Active Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7
	✓	✓	×	×	×	✓	×
3. Action/Reaction pairs	AR1	AR2					
	✓	✓					
4. Concatenation of influences	CI1	CI2	CI3				
	×	×	✓•				
5. Other influences on motion	CF	OB					
	×	×					
5.1 Resistance	R1	R2	R3				
	✓•	×	×				
5.2 Gravity	G1	G2	G3	G4	G5		
	×	×	✓•	×	×		

a. A '•' in a cell means that only one of a number of same-category misconception indicators was chosen.

7.2.1.2 Introductory questions

Consistent with her poor FCI score for gravity, Joanna describes gravity phenomenologically, with no coherent use of Newtonian argument[21] (N0), and has no causal model of gravity (-N4). Consequently, she is unable to correctly explain the gravitational attraction between the basketball and the Earth (-N4, -5G1, -5G3), and is confused about the nature of action-reaction forces between the basketball and the Earth (-N3.2 FCI), arguing that there are two forces that somehow interact: 'The gravity down and the gravity reacting from the Earth' (l:220). Her desire to use a formula (rather than *explain* what was happening) may be due to shallow learning of concepts (Brown, 1989) and/or an inability to contextualise her understandings (Gunstone & White, 1981), or perhaps, in Minstrell's (1994) terms, is a result of ontological and relational confusion about elements of the NFC and gravity (cf. Section 4.3 on page 102). Accordingly, she generally articulates sufficient (phenomenological), but not defining (Newtonian), responses about gravity in responding to these introductory questions[22].

7.2.1.2 (a) Gravity

Int: What do you think of when you hear the word gravity? Stu: The apple. Int: The apple? Stu: OK, Newton's apple! Yep.	*s+/d- No mention of scientific definitions, mathematical relationships, nor terminology – e.g. of Force, field or mass. No causal model for Gravity. (N0)*
Int: What's your best example of gravity other than that? Stu: Um. Someone falling off a cliff. Someone suiciding.... Gravity...usually objects falling due to gravity.	*s+/d-* *No causal model for Gravity. (N0)*
Int: Where do you find gravity? Stu: Find it? Int: Where is it? Stu: Ah, right. Where do you find it? I don't know general questions like this. I'll roll off a formula if you like! Gravity...gravity acts on everything, doesn't it? I'm sure it does!	*s-/d- Describes 'what' and not 'where'. Possible shallow learning of concepts (Brown, 1989) or decontextualisation (Gunstone & White, 1981) or preference for algorithmic/mathematical argument? (N0)*

21. other than the use of the term 'gravity'.

22. n.b. use of these two categories follows Keil's (1989) work on articulating properties of nominal kinds, but are used here only as meta-tags to describe the general nature of the discourse in terms of responding to the question/probe.

Int: How do you know when it's present?
Stu: Well you can't see gravity. But you can see things acting due to gravity.
Int: Like, what?
Stu: Pen falling off a table.

s+/d- Phenomenological response - possible ontological and relational confusion? (cf. Minstrell & diSessa, 1994).

7.2.1.2 (b) Projectile probe

Joanna neither explains, nor addresses, the distorted basketball path (Figure 6-12), apparently not recognising the non-parabolic trajectory (-K0.3, -5G3 FCI). She explains the basketball's falling in terms of an apparent action-reaction couple (-N3.1, -5G1 FCI), without being able to clearly articulate the model, and is confused about what her representation of it (Figure 7-2) actually shows.

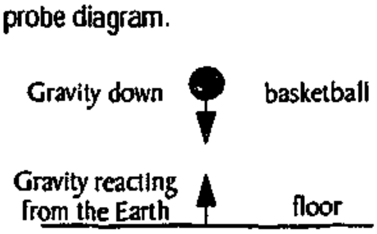
Int: Are you able to tell me about the arrows again?
Stu: I'm sorry. I really am. The gravity down and the gravity reacting from the Earth which is what my teacher in high school explained to me. I never really understood very well myself but I always believed her and it was about something was being...coming down from the Earth, on to the Earth and the Earth won't move as well. So if something was big enough, it would make the Earth move. I guess like the Sun.
Int: So that's why the basketball moves?
Stu: That's not why the basketball moves. Sorry. No. I'm trying to work that out. I can't explain it.

s-/d- -N3
Confusion over action-reaction forces (gravity 'reacting' from the Earth) and action-at-a-distance.

Possible problem with concatenation of influences (CI1 in Table 7-5).

No causal model for Gravity. (N0)
Lack of subject matter knowledge. (N0)

Figure 7-2: Joanna's projectile probe diagram.



7.2.1.2 (c) Summary

Consistent with her poor FCI scores on N2, N3, and gravity, Joanna demonstrates ...le understanding of gravity in these contexts, offering weak, confused, responses that are devoid of correct Newtonian argument (N0). These fundamental problems in articulating simple aspects of gravity (-5G1, -5G3 FCI) and the NFC (N0, -N3) may arise from either a fundamental lack of subject matter knowledge, or perhaps, in accordance with diSessa (1993b, p1), from an inability to contextualise and interpret understandings learned in a quantitative framework (cf. Gunstone & White, 1981).

7.2.1.3 Video Probes

NOTE: These probes explore a range of mechanics concepts and understandings in contexts based on falling and projectile motion, examining underpinning mechanics concepts (such as inertia and momentum) that might be used in explaining the planetary contexts, as well as the specific gravitational events in the cartoons.

7.2.1.3 (a) Homer's leap

Joanna determines that gravity was 'acting' (but does not explain what this means) as Homer rolled down the hill, that the leap as depicted is incorrect (+5G3), and that the sudden drop is unrealistic (but with no notion of impetus implied), with Homer '...defying the laws...' (l:109)[23] of gravity (without explaining this in Newtonian terms) as he flies of the cliff, and suddenly falls:

> It was like he was travelling just flat and it was like there was a hole in the bridge and he just fell straight through it. So... the shape wasn't right. (l:137)

When asked to identify aspects that showed the effect of gravity, she identified the sudden fall after the Ollie (l:145), and, after some uncertainty, Homer's fall from the ambulance. No other issues were raised. While demonstrating apparent awareness of projectile motion, her answers are devoid of Newtonian arguments (N0). This may be because of her general weakness with the NFC and its gravity contexts (Table 7-6 and Table 7-7).

23. Joanna's transcript line number for this quotation.

7.2.1.3 (b) Road runner probes

Note: This series of probes extends the situations contained in the Simpson's probe, and includes additional items on inertia and free fall, along with some video-clip specific items such as elasticity and rotational torque (which are not the essential features of these probes, but which serve to gain further insights into the participants' mechanics knowledge).

Joanna is aware that the video-clips depict erroneous motion, but it is unclear whether this awareness stems from Newtonian understandings or from an intuitive, or 'everyday' sense of what such motion should be like. She failed to comment on a number of significant events in the video clips (differential and variable rate of falling, rotation in free fall, and elastic rebound). Some events that she is not able to explain are described as being portrayed 'in a cartoon sense' (e.g., 1:114, 1:194), implying that she recognises their non-Newtonian nature, but is unable to explain them. It is not clear if this affects the nature of her responses; i.e., if she is responding in a consistent Newtonian or 'cartoon' sense to all of the probes, because in these interviews it is only possible to get a certain amount of information from the participants about specific events, and often (as in this case) what they mean, but do not say, is difficult to interpret.

Stu: (1:172) There were heaps that were wrong. Int: Can you tell me them?	*Awareness of errors in the video clips.*
Stu: The way the curve and … with the Road Runner and that going straight and the same with his pattern, again and being stuck in the air, well, the chances of that is very impossible.	*Identifies extreme acceleration around the cliff and incorrect horizontal projection off the cliff (as per Homer).* (NΘ)
Stu: When he got stuck in the ski thingy's. Well I don't think that would happen. I don't know if that's due to gravity, but...anyway.	*Confusion over collision/impaling with cliff face - inertial aspects not clearly articulated.* (-N1). *Not certain of role of gravity.*

Stu:	… when the first dart hit the balloon, he sat there and he sat in his little basket and the strings went down first and then he went down … and then when he had the parachute the same things happened. He just stopped in mid-air and the strings...I don't know how you would explain...like they had gravity on it and he didn't for a while, maybe, I guess from a cartoon sense.	Correctly identifies inertial and gravitational contexts as incorrect, but without any causal model or formal description(-5G3) (NΘ). Selective action of gravity - acts at different times on different objects? (cf. Watts, 1982, framework 7)
Stu:	And then when he was on the rock and it broke off, that was still hanging there in mid-air, so that just defies gravity. But he jumped over the other one and the rest of it decided to fall and with the weight, the weight was below him and it was falling but then he suddenly... it was above him, and he suddenly moved it down so it was on top of it. So, no that wouldn't happen either.	Again, correctly identifies inertial and gravitational contexts as incorrect, but without any causal model or formal description (-5G3) (NΘ)
Int:	Were there any right things?	Aware of, but cannot articulate, Newtonian reasons why? (NO)
Stu:	Um. Not really, I don't think.	

7.2.1.4 Planetary computer probes

NOTE: these probes examine the participants' knowledge and understanding of planetary gravity and motion in radial gravitational fields (the key context of the VCE physics curriculum described in Chapter 2). Knowledge of Newton's law of universal gravitation and Kepler's laws are essential for participants to readily understand and respond to theses probes.

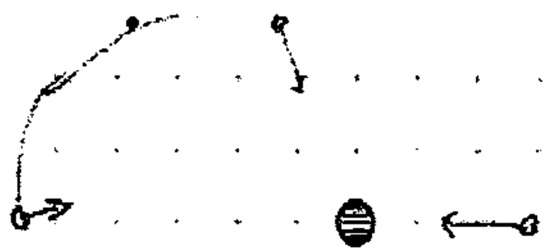
7.2.1.4 (a) Single-planet probes

Joanna determines that terrestrial gravity is responsible for deflecting the asteroids (1:274), but gives no formal causal model (-N4, -5G1 FCI). Gravity (around the Earth) forms a 'capture zone' (-N4, -5G1 FCI) with a finite boundary where gravity stops (1:299)[24], trapping asteroids which then get drawn towards the Earth, and can then collide with it (1:299). She gives no reason for this belief, and becomes confused on further probing. She correctly represents gravitational force on an asteroid (Figure 7-3) with radial vectors of appropriate magnitude[25], and with variable speed[26] throughout the orbit.

24. cf. Watts (1982) and Stead & Osborne (1980), where similar, but different, models are described.

25. i.e., for a freehand drawing.

Figure 7-3: Joanna's representation of gravity on an orbiting asteroid.



Joanna's responses make no use of Newtonian or 'Keplerian' arguments (N0, -N4), making it difficult for her to predict possible orbital parameters, and to discuss the effect of distance on asteroid motion in a systematic manner — resulting in a 'hit or miss' approach to several of the probes that require the manipulation of variables.

7.2.1.4 (b) Dual-planet probes

In probe G4, Joanna correctly predicts that linear motion will occur (but does not predict the oscillation) as a result of superposition of the two gravitational forces (+S4.1 FCI):

> Well if the planets are equal mass, and if the asteroid's going through at the same, like straight through the middle, the gravity from both planets will try and draw the asteroid towards it, won't it? (1:488)

but has difficulty in explaining why this should be (-N4, -S4.1,-S4.2 FCI):

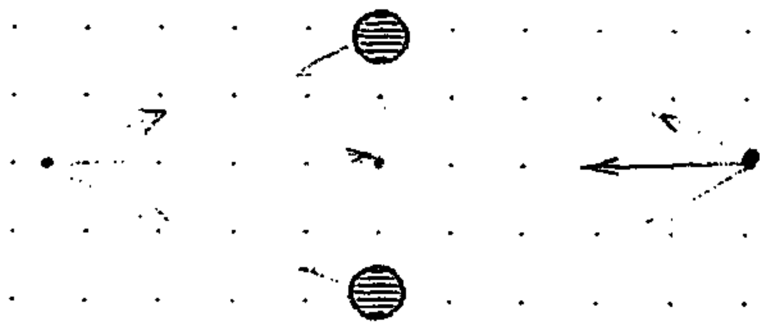
> Because if they. .I don't know, I just did. I just thought they would. (1:504)

Subsequently, as in Figure 7-4, she identifies equal gravitational forces acting from each planet, which cancel each other in the vertical direction[27] (1:567) because of the unique geometry of the situation (+S4.2 FCI) (1:544). She is initially confused over the reason for the asteroid's oscillation, suggesting that it is both *pushed* and pulled by gravity at different times (-N4):

26. as opposed to velocity.
27. i.e..as in Figure 7-4.

> It's being drawn...it's slowest on each end and it's pretty quick in between the planets, so I guess from when it runs it's being drawn in by both planets, I guess, and then pushed away. ... It's an equal sort of... (1:520).

Figure 7-4: Joanna's depiction of the origin of linear motion.



Subsequently, she realises that gravity from each is attracting the asteroid at all stages of its motion:

> Because once it's pulled...once it goes...Like it gets pulled towards the planet so it speeds up and as it goes past, it's trying to be pulled back, so it slows down. (1:576)

In probes G5 and G6, Joanna identifies distance between masses as being an important factor in the force exerted between them (i.e., on the asteroid), but remains confused about what this force is (-N4) (1:672-677):

Int: So you're saying that it diminishes as it gets out to here?
Stu: I don't know. I think that's the pull. I don't know if that's gravity.
Int: Sorry, that's the pull ... but not as gravity?
Stu: I don't know. I've never thought about it.

This demonstrates her obvious and fundamental confusion about gravity in planetary (and other?) contexts. She is unable to relate the vector representation of 'force' to 'gravity', seeing them as two separate entities (-N4) which somehow act, apparently independently, on objects near a planet (in this case).

7.2.1.5 Vector probes

Consistent with her poor FCI score for kinematics, N2, and N3, Joanna's responses to these probes shows that she has difficulty in interpreting dynamic representations of vectors, and particularly, the relationship between tangential velocity and acceleration in rotational (orbital) contexts.

Stu: Well it's going around in its path and when it reaches the back of the Earth it's being...there's more force on it I guess, that's why there's more arrows... The arrows are bigger, yeah. Um...they are close together...Why does it go like that thing at the bottom though?...	Probe 1 (Figure 6-51 on page 236) Confused by changing magnitude and direction of gravitational force vectors and why their spacing changes during the orbit.
Um...From the starting point as it moves closer to the Earth the gravitational force on the asteroid increases until it gets probably I'd say to the back of the Earth here and it peaks and it...I don't know why it's flat though. <'flat' = vectors horizontal> Int: So there's no gravitational force on the asteroid?	Appears to have a Cartesian view of the probe - "falls" down the screen - bottom motion (vectors "up") is therefore confusing(?) Failure to understand basic vector concepts and/or representations.
Stu: I'm not sure. And then as it comes back around the force lessens again so it drops...it increases steadily high, it doesn't decrease as much. I don't get this bit in the middle.... I don't know how it goes back on itself but anyway.	Demonstrates confusion with what is being represented in the probe - does not understand why orbital motion occurs. (-N4, -K)

The inclusion of velocity and acceleration vectors in probes 2 and 3 caused similar problems:

Stu: Well around the back here, the velocity is on the path but as it goes further away from the planet, it's not. I don't know why!	Position and velocity confused? (-K1 FCI) - expects velocity vector to be tangential to the path.
Int: What about the acceleration vectors? What causes that acceleration?	No comment on gravitational force, nor awareness of N4 (-N4, -5G1)
Stu: Well the asteroid starts off moving obviously, but I think once it gets pulled in to the...it's that capturing stuff again. That whole pull, the pull, the gravitational pull.	Resorts to her 'capture zone' model. Apparently recognizes that the force creating the acceleration is due to gravity.

Responses to the subsequent probes in this series elicited similar issues to those raised above.

7.2.2 Susan

Susan is undertaking major studies in both English Literature and Mathematics, and a sub-major study in Physics. Susan's self-assessment of her knowledge of Physics (in general), and of the area of Mechanics in particular were both 'average to good'. Her other tertiary science studies are first-year Chemistry and first-year Biology. Susan's physics background is considered to be normal, with three years of studies in Physics completed (Table A-3 on page 3).

7.2.2.1 FCI questions

The FCI data (Table 7-6) indicate that Susan has very weak understandings of the NFC across all categories, particularly with N1 and N3. Her understanding of gravity (Table 7-7) (as measured by the FCI) is also poor. Susan's FCI-predicted misconceptions (Table 7-8) provides further evidence of her difficulties with the NFC, suggesting the likely use of impetus models (I3, I4, I5), active force (AF1), action-reaction forces (AR2) and concatenation of influences (CI2, CI3). With her lack of understanding of the NFC, and the potential misconceptions listed here, it is highly unlikely that she will be able to offer satisfactory responses to most of the probes.

Table 7-6: Susan - FCI results by category.

FCI category	0 K	1 N1	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	3	0	1	0	1	5	24%
Percentage	50%	0%	50%	0%	25%	31%	

Table 7-7: Susan - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	2	0	1
Percentage	33%	0%	50%

Table 7-8: Susan - predicted misconception areas (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	K1	K2	K3				
	×	×	×				
1. Impetus	I1	I2	I3	I4	I5		
	✓•	×	✓	✓	✓•		
2. Active Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7
	✓	×	×	×	×	✓•	×
3. Action/Reaction pairs	AR1	AR2					
	✓•	✓					
4. Concatenation of influences	CI1	CI2	CI3				
	✓•	✓	✓				
5. Other influences on motion	CF	OB					
	✓•	×					
5.1 Resistance	R1	R2	R3				
	✓•	✓•	×				
5.2 Gravity	G1	G2	G3	G4	G5		
	×	×	✓•	✓•	✓•		

7.2.2.2 Introductory questions

Consistent with her low level of understanding of the NFC as diagnosed by the FCI, Susan's responses are simplistic[28] and characteristic of a lack of subject matter knowledge, demonstrating confusion about the most basic aspects of gravity, and lacking any reference to causal models or to Newtonian mechanics (NΘ).

28. as with the previous participant.

7.2.2.2 (a) Gravity

Int: What do you think of when you hear the word 'gravity'? Stu: Um I don't know, ... why things fall I guess. Int: If I said you were going to teach gravity next week, what would you think of? Stu: Get me a book!... um ... what would I think of ...um ... I have no idea!	*s-/d- No mention of scientific definitions, mathematical relationships nor terminology. No causal model for gravity. (NΘ) Lack of knowledge - content or contextual(?) - evident.*
Int: What's your best example of gravity? Stu: Ah I don't know. Drop something off my desk I guess. That's more PE than gravity isn't it, when you drop it off a desk?	*s+/d- Confusion of concepts - Energy/Work versus Force (gravity)? -N1, -N2*
Int: Where do you find gravity? Stu: Everywhere! Int: How would you know if gravity was there or not? Stu: I think gravity exists between ... gravitational force exists between all masses so ... I don't necessarily think you would be able to see it... Int: And how could you test for it? Stu: Test for it? Depends if you had really great equipment.	*s+/d- Unable to contextualise response to previous question (Gunstone & White, 1981)? +5G3 (FCI) - nature of gravity Shallow learning of concepts and contexts (Brown, 1989)? (NΘ)*

7.2.2.2 (b) Projectile probe

Susan's apparent lack of understanding of many Newtonian concepts appears to manifest itself in the (overall) transcript as short, descriptive or phenomenological responses (as below), and an unwillingness to engage in protracted discussions on the areas being probed:

Int: On this diagram can you draw something to indicate what gravity is doing? Stu: Well gravity is acting on all ... everything...<pause> Int: So its everywhere in there? Always acting on the ball? Stu: Yes! Int: Is that why it falls down? Stu: Yes! ... Int: ... Is that all you have to say about this? ... About the gravity, the ball's motion .... Stu: Yes! <emphatically>	*s-/d- No causal model for gravity (NΘ). No mention of scientific or mathematical terminology. Confused 'dual-mode' of action for 'two kinds' of gravity (Figure 7-5) Possibly related to weak understandings of both NFC and gravity (Table 7-6 & Table 7-7).*

Figure 7-5: Susan's projectile probe diagram.

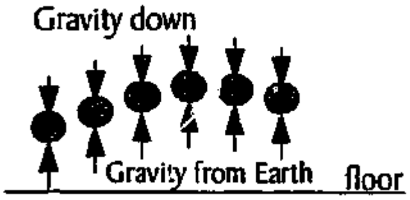


Figure 7-5 depicts a gravity model that shows major conceptual problems with gravity and N3 (cf. Figure 4-9), in which the basketball is acted on by two separate gravitational forces (cf. Joanna - Figure 7-2 on page 250) — gravity acting downwards, and some opposing force from the Earth acting upwards; perhaps representing an 'intrinsic' buoyancy[29] force of gravity, or erroneously depicting (by acting on the ball - as drawn) the force of the ball on the Earth (1:221). Presumably, as with -CI1[30] (largest force determines motion) their relative strengths vary in some systematic way during the time the ball is moving, with 'gravity down' finally overcoming the 'gravity from the Earth'.

7.2.2.2 (c) Summary

Susan's weakness with the NFC is confirmed here as she offers weak, apparently confused, responses that are essentially devoid of Newtonian argument (NΘ), and a gravity model that exemplifies confusion about gravity as a force between masses, (-N4, -5G1 FCI) and reaction forces (-N3,+5G2 FCIM).

29. Stead and Osborne (1980) found that some school students believed that gravity was responsible for both reaction and buoyancy forces.

30. See Table 6-7 on page 190.

7.2.2.3 Video Probes

These probes confirm Susan's poor understandings of the NFC and gravity when she is again unable to describe projectile motion as 'parabolic' (-5G3 FCI), and cannot explain, in Newtonian terms, the events depicted in these probes (NΘ).

7.2.2.3 (a) Homer's leap

Susan could not explain the nature of the initial accelerated motion down the hill (-5G1 FCI), but correctly identifies that Homer's path is wrong ('too flat'), as is the sudden fall, but is not able to explain why this is so in terms of Newtonian mechanics (-5G3 FCI):

> Yeah, it was wrong. Ah...Coming off there, I really don't think you would just go straight across there and then straight down – not at right angles. I really don't. ... What else was there .... He spent a long time in the air! (1:57)

She also questions the differential rates of falling at the end, but appears uncertain as to why this would happen, arguing that 'in real life', air flow would create lift that would produce 'normal' parabolic motion (-5G3).

> I am trying to think if it would really land on him. He's come off ... in the cliff they had him falling straight down,... so if he was falling straight down, on top of the skateboard, you would think it would be under him. Which doesn't necessarily mean it would happen in real life... In real life, I still think he would get more ... lift ...would go up and ... more like the projectile that we are used to seeing... would come down and ...don't know if he would stay on top of it! (1:82)

Susan's responses are symptomatic of a poor understanding of the NFC and gravity (cf. Table 7-7), and her apparent lack of a Newtonian gravity model (Figure 7-5) to use as a basis for argument.

7.2.2.3 (b) Road runner probes

Susan's responses are again short, and devoid of Newtonian arguments (N0). She identifies an incorrect projectile path (+5G3 FCI) in the first probe (Figure 6-24 on page 215), but does not provide a causal reason as to why it is wrong (-N2.2 FCI). Several incorrect scenarios in which objects fall (or remain stationary) in other probes were also briefly commented on (e.g., Figure 6-25 on page 216), but no scientific critique was provided (NΘ).

7.2.2.4 Planetary computer probes

Susan describes a point-to-point gravity model between masses in which speed can 'overcome' the effects of gravity, and masses 'fight each other' to establish a gravitational force.

7.2.2.4 (a) Single-planet probes

In Susan's view, gravity exists only between the planet and asteroid (-N4), with an equal force acting on each, producing an 'effect' (acceleration?) which depends on the size (cf. mass) of the object and their distance apart (-N4). Speed can 'counteract' the gravitational force (i.e. reduces the apparent deflection); an argument that suggests difficulties with vector quantities and basic projectile motion concepts. She has an animistic view of gravity as a kind of 'active agent' of the particular mass being discussed (+5G2 FCIM) — as opposed to the force between the masses which 'fight each other' (+AF4):

Int: You can see on the screen ...how fast it moves around the planet; how slow it goes up the end there. Can you tell me anything about what it indicates?
Stu: Well maybe ... um hmm ...maybe further away from the planet there where it's going slower, you've got the path where the asteroid was taking... and the planet's trying to pull it back in with its own gravitational pull, so they are fighting each other and it slows down ... but when it's closer to the planet then the planet's just winning, making it so what it wants it to do.

This indicates a fundamental lack of understanding of gravity (-5G1 FCI), inertia, and action-reaction pairs (+AR2 FCIM), as well as Kepler's laws and N4. Susan's responses are consistent with her low score on the FCI. Her fundamental conceptual difficulties with these aspects of gravity and the NFC are subsequently confirmed:

Int: Why does it move so fast when it goes around behind the planet?
Stu: Um, ...
Int: Do you have any idea?
Stu: No, I don't really! Apart from ...just ...they're the only forces I can think of that are due to the gravity. Must be something to do with the gravity! (1:297)

7.2.2.4 (b) Dual-planet probes

Despite a poor score for superposition on the FCI, Susan correctly predicts linear asteroid motion as a result of equal gravitational forces from each planet (+S4.1 FCI), and suggests that the asteroid might stop midway between the planets as a result of cancelling forces (+S4.2) (as in Figure 7-6).

Figure 7-6: Force acting on the asteroid on each side of the planets.

She has difficulty in using precise language or Newtonian arguments (NΘ), and prefers to use pseudo-phenomenological statements such as stating that the motion is because 'that is the direction it is travelling in' (+A1) (l:321) and 'because it's sort of halfway between them' (l:330).

Int: Can you indicate the direction and size of the forces on the asteroid ...?
Stu: ... to the planet, (it) would be pushed towards (it) - gravity would exist both ways... (l:327)

Here she is confused about gravitational force acting on the asteroid — does it 'push' (cf. contact force?) or 'pull' (cf. gravitation?). Similarly, she is confused about other basic dynamics concepts such as harmonic motion and N2, and cannot describe, in Newtonian terms, the motion or acceleration of the asteroid as it reaches the maximum amplitude of its oscillation:

Int: So the asteroid is oscillating between the 2 of them, along the line?
Stu: Yeah. That's really weird because .... Like at this point it's pulling it back now, so the gravity is pulling it back. Then it gets flung the other way. Maybe what's happening is that the asteroid is building up its own sort of velocity... And it sort of comes back ... that's why it goes past. I don't know, maybe that's why it goes past that centre point. I thought it would just stop in the middle. (l:339)

In probe G4 she uses a 'parallelogram of forces' approach to predict the resultant force on the asteroid (+S4.1 FCI), and hence its likely initial path, but does not relate it to the previous oscillating asteroid probe.

7.2.2.5 Vector probes

The use of explicit vector representations helps Susan to clarify some of the issues from the previous probes:

> The acceleration is greater when it's on the closest side! Um, Hmm F = ma! Um, perhaps ... Ok, that makes sense, doesn't it? Cause if the gravitational force keeping it in is greater when it's closer, it could accelerate more when it's closer; that's why it's going faster. (l:421)

With the multi-planet probe (Figure 6-52), the vector representation assists in increasing her understanding of the complex motion:

> And as it moves out of the way … the asteroid perhaps …has still got some of its momentum or … so it's got maybe some sort of … tendency to continue in this direction and then um, starts to be attracted. The gravitational attraction between the pink planet and the asteroid starts to come into effect[31]. (1:452)

7.2.3 Denise

Denise is undertaking a double-major mathematics sequence (mathematics and statistics), and a sub-major study in Physics. Denise's self-assessment of her knowledge of Physics (in general) was 'better than average', and of the area of Mechanics in particular was 'weak to average'. First-year Biology is her only other tertiary science study. Her physics background is considered to be normal, with three years of studies in Physics completed (Table A-4 on page 4).

7.2.3.1 FCI questions

The FCI data (Table 7-9) indicate that Denise has a good understanding of the NFC, suggesting that she should have little difficulty with any of the probes. Her understanding of gravity (Table 7-10) (as measured by the FCI) is excellent. Denise's FCI-predicted misconceptions (Table 7-11) suggest the likely use of Newtonian models in most contexts, with some possible difficulties[32] with action/reaction pairs (AR1, AR2) and superposition (CI2, CI3), and likely difficulties in dealing with vector addition (K3).

31. taken to mean that it causes a change in motion; not that there is a point at which it suddenly starts to act.

32. nb. Hestenes' caution about 'the odd incorrect response' may not be indicative.

Table 7-9: Denise - FCI results by category.

FCI category	0 K	1 N1	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	4	7	2	3	3	15	81%
Percentage	67%	88%	50%	75%	75%	94%	

Table 7-10: Denise - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	6	2	2
Percentage	100%	100%	100%

Table 7-11: Denise - predicted misconception areas[a] (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	K1	K2	K3				
	✓•	×	✓				
1. Impetus	I1	I2	I3	I4	I5		
	×	✓•	×	×	×		
2. Active Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7
	✓•	×	×	×	×	×	×
3. Action/Reaction pairs	AR1	AR2					
	✓•	✓•					
4. Concatenation of influences	CI1	CI2	CI3				
	×	✓•	✓•				
5. Other influences on motion	CF	OB					
	×	×					
5.1 Resistance	R1	R2	R3				
	×	×	×				
5.2 Gravity	G1	G2	G3	G4	G5		
	×	×	×	×	×		

a. A '•' in a cell means that only one of a number of same-category misconception indicators was chosen.

7.2.3.2 Introductory questions

Denise's responses here do not reflect her good FCI score, with weak or incorrect statements (in accordance with diSessa, 1993b, p1) possibly indicating shallow learning of concepts, laws, etc., or an inability to contextualise existing knowledge to 'new' situations (cf. Linder, 1993; Palmer, 1997).

7.2.3.2 (a) Gravity

Int:	What do you think of when you hear the word 'gravity'?	s-/d- No causal model etc. (as with the previous participant). Possibly a learned example, but with the meaning forgotten. (N0)
Stu:	The Moon.	
Int:	Why the Moon?	
Stu:	I'm not actually sure.	
Int:	What do you think of as being gravity itself?	
Stu:	A force of attraction.	s+/d- No causal or explanatory model. (N0)
Int:	A force of attraction? And where do you find it?	
Stu:	It's all around us.	
Int:	Suppose we could find a region of space somewhere and we wanted to test to see if there was gravity there, how could we find a way to test for gravity?	
Stu:	You possibly … throw … something … see if it goes through?	s-/d- Confuses gravity (gravitational field?) with a kind of force-field barrier? Notion of penetration, as opposed to 'falling', may be confused with, for example, escape velocity of a rocket - need to 'break away' from the Earth? (N0)
Int:	Then what would that tell us?	
Stu:	Tells us there is no force holding it back.	
Int:	And that would be indicative of gravity, is that what you're saying?	
Stu:	Not really but it's an idea. It might be weak gravity.	

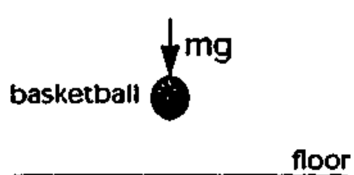
7.2.3.2 (b) Projectile probe

Denise determines that gravity acts continuously on the ball, but is not sure if gravity is a force as the motion pulls the ball to the ground (-K0.3 FCI, +AF2 FCIM). She is confused about the nature of gravity and projectile motion, with possible active force misconceptions, and demonstrates inconsistency or lack of coherence in describing the nature of gravity — 'Gravity's actually pulling it down, so it can't be a force.' (l:257) versus '…that's the force of gravity pulling them down.' (l:260). Possibly this is a strong example of diSessa's notion of disconnected, or poorly connected, 'knowledge in pieces' (diSessa, 1988).

Int:	Is there gravity acting here? (1:240)	
Stu:	<long pause> You can see that it is because it's actually, the projectile is actually, ... the motion's actually pulling the ball towards the ground so...	s-/d- Notion of motion as an agent - active force misconception here? (+AF2, -KO.3 FCI) (NΘ).
Int:	OK, so the motion is pulling it towards the ground. Is that an indication of gravity?	
Stu:	Yeah.	
Int:	OK. Can you draw on the diagram somewhere to show me how gravity acts?	s-/d- Confusion over cause and effect. (refers to Figure 7-4)
Stu:	Gravity's actually pulling it down, so it can't be a force.	Force-gravity confusion here (cf. above). (NΘ)
Int:	Alright. Do you want to draw that on the diagram? Right.	Draws correct 'mg' vector.(I)
Stu:	So ... that's the force of gravity pulling them down.	Inconsistent/contradictory to above.

In Figure 7-4, Denise indicates both the magnitude and direction of gravity, and indirectly recognises that it is the only force acting on the ball, and that it is constant over the whole time of motion. Whether gravity is seen as a 'pushing' or 'pulling' force is not clear as drawing the vector at the top may or may not be significant (unlike in the previous participant's diagram).

Figure 7-7: Denise's projectile probe diagram.



7.2.3.2 (c) Summary

Denise's responses here are in complete contradiction to her FCI score for gravity (100%), and high overall FCI score, showing confusion over the nature of gravity (-N4, 5G1 FCI) — whether it is a force between masses, or an active force created by motion (-N1, -5G1 FCI; +AF2 FCIM). Her graphic representation, however, shows an apparently correct vector of magnitude 'mg' acting vertically on the ball. Her responses are weak (in Newtonian terms), inconsistent, or contradictory, and frequently fail to make any use of Newtonian constructs (NΘ). This is perhaps due to an inability to contextualise existing NFC knowledge to real-world contexts.

7.2.3.3 Video Probes

In both of these probes, Denise partly understands what is happening, and argues from a Newtonian perspective, but appears to have difficulty with N2 and mass (-5G2 FCI). In contrast to responses above (Section 7.2.3.2), she identifies gravity as a force.

7.2.3.3 (a) Homer's leap

Denise has difficulty in explaining Homer's motion down the slope:

> Well. Um...because he's got a mass, so he's got some sort of momentum and the momentum is like carrying him along. So...(1:188)

but identifies the incorrect projectile motion and offers what appears to be a sound Newtonian reason for it, though not necessarily stated in those terms (1:158):

Stu:	That was wrong!	
Int:	OK. Why?	
Stu:	Because he's got forces, gravity, pulling him down and also he's still got horizontal motion across the gorge.	s+/d- +K0.5? (FCI)
Int:	OK. So he should have a different path?	
Stu:	Yeah. It should be more a curved path. And right at the end when he actually fell, he just went straight down rather than curving all the way down.	+5G3 (FCI)

However, she clearly misunderstands N2 and gravity, arguing that objects with less mass would travel further[33] (because they would take longer to fall) (1:171):

Int:	At the very end, when he was lying in the bottom of the gorge, the skateboard landed on his head.	
Stu:	That wouldn't happen at all.	s+/d- Correct answer based on 5G2 (FCI)
Int:	Why not?	
Stu:	Well it's much lighter mass, so it would continue much further along.	-5G2 (FCI), +5G3 (FCIM) -N2 (cf. previous).

7.2.3.3 (b) Road runner probes

Denise again identifies the incorrect projectile motion, with objects undergoing projectile motion having both horizontal and vertical velocity components, but appears uncertain about exactly what that means (I:205):

> The ski poles wouldn't go... continue straight down, in a straight line down. They would also... they would generally fall down but they would still have some momentum or some component of velocity going in a horizontal direction so...

describing an apparently mass-dependent acceleration (-5G2) (cf. Section 7.2.3.3 (a)) in this context (I:236):

> It depends on weight but generally they're going to fall down I guess at the same sort of speed if they had same sort of mass.

7.2.3.4 Planetary computer probes

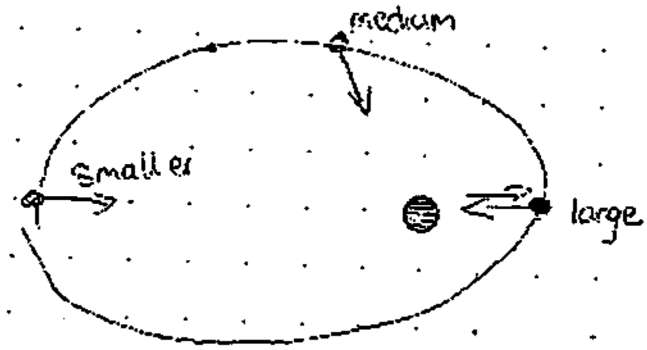
Both gravity and a speed-dependent 'attraction force' act on asteroids (-N4, -5G1) to change their path. Gravity is a unidirectional force exerted by the planet on the asteroid (Figure 7-8) that varies with distance in an unspecified manner.

7.2.3.4 (a) Single-planet probes

Gravity is identified as a radially directed force between the asteroid and planet (I:313), with a magnitude that varies with distance (but not as with N4) as in Figure 7-8.

33. i.e., horizontally during projectile motion.

Figure 7-8: Denise: variation of gravitational force during orbital motion.



Confusion about motion and gravity is evident, with the asteroid's motion apparently being indicative of 'weak gravity' because it is not (explicitly) being drawn into the planet (+AF2? FCIM):

> Well as you are moving across, it would be relatively weak gravity (l:269)

She differentiates between gravity and an 'attraction force' that (again) appears to be speed dependent (l:326):

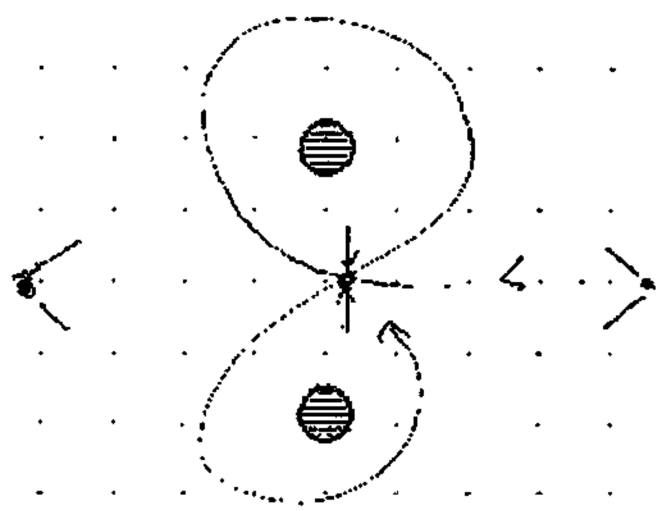
> Well it's moving slower and it's closer to the planet, then there would be a stronger attraction force and gravity you'd assume to be stronger.

Subsequently she correctly describes N4, but does not relate it to the previously discussed probes. In explaining orbital motion, she describes the variation of velocity and force without referring to N4 or Kepler's laws, arguing that because the centripetal force, and hence centripetal acceleration, on the asteroid varies, the tangential velocity will also vary, but no relationship between these quantities is described (-N4, -K) (l:558).

7.2.3.4 (b) Dual-planet probes

Consistent with her FCI score for superposition and gravity, Denise correctly describes the nature of the forces on the asteroid during oscillation (probe G4), why the speed of the asteroid varies, and predicts the binary orbit in probe G6 (Figure 7-9). This suggests that, as part of her understanding of superposition, she has a good understanding of how to represent and interpret vectors in such contexts.

Figure 7-9: Denise: prediction and explanation of binary orbit



Int: Why does it do the figure eight in this case and it wasn't in the first place?
Stu: Because it was actually at one stage closer towards one of the planets.
Int: And so?
Stu: And so the force of attraction actually attracted it closer towards the planet so it circled it and as it got further away the other planet pulled it towards that so then traced out a figure eight.

Denise, however, does not generally use detailed Newtonian arguments, preferring general descriptive statements. How well she really understands the NFC is not clear from these, other than that she can apply relevant aspects to describing contexts such as those presented here.

7.2.3.5 Vector probes

In accordance with her apparent comfort in using vector representations, Denise found little, if any, difficulty with these, explaining what was occurring, and stating that they confirmed her previous explanations, and were useful in helping her to better visualize a dynamic representation of the events.

7.2.4 Alex

Alex is undertaking a double-major Mathematics sequence, and a sub-major study in Physics. Alex's self-assessment of her knowledge of Physics (in general), and of the area of Mechanics in particular, were both 'average'. Her other tertiary science studies consist of a two-year sequence in Earth Science. Her physics background is normal, with three years of studies in Physics completed (Table A-5 on page 4).

7.2.4.1 FCI questions

The FCI data (Table 7-12) indicate that Alex has a moderate understanding, (but highly variable across categories), of the NFC. Her understanding of gravity (Table 7-13) (as measured by the FCI) is good, with some potential difficulties[34]. The obvious predicted difficulties with N2 and N3 suggest that she should have problems with many of the probes. Consistent with this weakness, Alex's FCI-predicted misconceptions (Table 7-14) suggest the possible use of Impetus models (I2, I3, I4), and difficulties with action/reaction pairs (AR1, AR2), active force (AF1), and resistance (R2).

Table 7-12: Alex - FCI results by category.

FCI category	0 K	1 N1	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	4	6	1	1	3	13	67%
Percentage	67%	75%	25%	25%	75%	81%	

34. nb. Hestenes' caution about 'the odd incorrect response' may not be indicative.

Table 7-13: Alex - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	6	2	1
Percentage	100%	100%	50%

Table 7-14: Alex - predicted misconception areas[a] (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	K1	K2	K3				
	×	×	×				
1. Impetus	I1	I2	I3	I4	I5		
	×	✓•	✓•	✓•	×		
2. Active Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7
	✓	×	×	×	×	✓•	×
3. Action/Reaction pairs	AR1	AR2					
	✓	✓					
4. Concatenation of influences	CI1	CI2	CI3				
	×	×	×				
5. Other influences on motion	CF	OB					
	×	×					
5.1 Resistance	R1	R2	R3				
	×	✓	×				
5.2 Gravity	G1	G2	G3	G4	G5		
	×	×	×	×	×		

a. A '•' in a cell means that only one of a number of same-category misconception indicators was chosen.

7.2.4.2 Introductory questions

Alex's responses are consistently brief, and (except for the first extract below) are usually structured on Newtonian mechanics.

7.2.4.2 (a) Gravity

Int: What do you think of when you hear the word "gravity"?	
Stu: Ah... Things falling ... accelerating...	N0
Int: So where do you find gravity?	s+(?)/d-
Stu: Everywhere.	*No formal definition or causal model*
Int: And how do you know when its present?	*Decontextualisation(?) (Gunstone & White, 1981)*
Stu: You are not aware of it ... but you know its there!	*No linkage to previous response.*

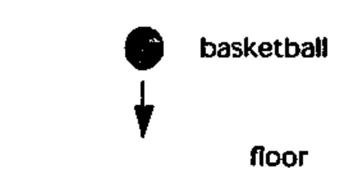
7.2.4.2 (b) Projectile probe

Alex concisely describes the problem, giving a causal mathematical model for the expected (correct) motion, but frequently refers to 'falling' rather than 'accelerating'. However, she uses g[35] correctly in explaining the mathematical model. It is not clear if this is due to incorrect or imprecise language use, or to a conceptual problem.

Int:	Where does gravity act here?	
Stu:	Everywhere. It's acting on the ball all the time, pulling it down.	s-/d- pulling vs accelerating.
Int:	So how does that explain the shape of the ball's path?	
Stu:	Well, when he throws it, the ball "falls" because it experiences a gravitational force, and there is no opposing force, so it falls. Hmm it doesn't fall much in the first bit, so maybe its going very fast... but it shouldn't fall there so quickly. I think the picture is wrong.	s-/d- no discussion of acceleration +N1,-N2(?) Identifies problem with path +5G3 (FCI)
Int:	How is it wrong?	
Stu:	Well if it is really a normal shot, it would follow the projectile motion ... the equation um ... $S=v_0t+½at^2$ and then it would be a parabola, because S is the height in this case, and 'a' would be g... gravity ... $9.8m/s^2$. Yeah. So the shape is not symmetrical – see it suddenly falls here and that's wrong. The ball should always be falling. ... It looks as if the ball suddenly hit something, or as if gravity just started acting there.	relates symbolic (mathematical) model to graphic representation. possibly 'fluctuating between intuition and algorithm' (Watts, 1980)

In Figure 7-10, the arrow represents gravity acting on the basketball, but there is no indication (here) as to whether it represents g (acceleration) or mg (force).

Figure 7-10: Alex's projectile probe diagram.



35. i.e., the acceleration due to gravity: ≈ $9.8 m/s^2$

7.2.4.2 (c) Summary

Alex's responses here are grounded in Newtonian mechanics (not always made explicit), make use of mathematical models, but suffer from imprecise use of language, resulting in descriptive responses which are neither satisfactory (s-) nor defining statements (d-) about the concepts under examination.

7.2.4.3 Video Probes

Alex has a clear Newtonian understanding of these gravitational events, determining that gravity, acting constantly (+5G1 FCI), is both thc cause of Homer's roll down the hill, and the reason that (a) that the various trajectories should have been parabolic (+N2.2; +5G3 FCI), and (b) that all of the falling objects would have accelerated at the same time and rate, regardless of their mass (+5G2 FCI).

7.2.4.3 (a) Homer's leap

Alex readily provides a causal model for the motion (+5G1) that explains why the trajectory is wrong:

> Well, when he falls, there is a gravitational force, mg, acting on him all the time, so he falls ... rolls ... ah, accelerates down the slope because there is a component of it acting parallel to the slope. And when he goes off the cliff it is still acting on him, so he should fall like in projectile motion. This looks like gravity just started there! (1:9)

She uses N2 to explain why the Ollie is not possible:

> I think that can't happen because it would accelerate away from him if he applied a force to it - it's falling too. (1:14)

7.2.4.3 (b) Road runner probes

Alex determines that the model above applies to these events, and that the trajectories depicted here are wrong for the same reason as in the previous probes, and that the elastic deformation would not happen because:

> Well the stretching wouldn't happen - gravity would act equally on his body which is pretty strong, inelastic, so he would move all at once. That's wrong, yeah! (1:22)

She considers both the rotational and elastic rebound events to be unlikely — the former because of the absence of an obvious torque, and the latter because the bow (apparently) would not be able to store enough energy to do adequate work on him to prevent his collision with the Earth (n.b. he strikes the ground first).

> I don't think you could have enough energy in the bow to do that … to overcome the kinetic energy he had[36]. (1:37)

There is no mention of the magnitude of the impulsive force and resultant acceleration during the impact, and the subsequent effect on the falling objects.

7.2.4.4 Planetary computer probes

Alex determines that gravity, while 'always existing', manifests itself only as a point-to-point force[37] between pairs of objects (1:206) (-N4), and is created (i.e., begins to act) only when objects are brought close together (1:233); i.e., a limited-range 'zone of influence model' around the planet[38] (in which gravity presumably

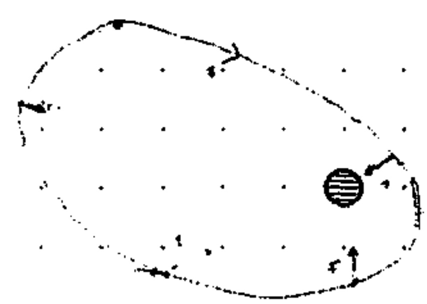
36. Presumably, the potential energy stored in the bow, by virtue of it being drawn, would be released to counter the force that Wylie would exert on the bow string during the collision i.e., a trampoline like effect, but with a single string.
37. i.e., as opposed to a gravitational field.
38. i.e., somewhat similar to the notion that gravity stops at the edge of the atmosphere (Bar et al., 1997; Stead & Osborne, 1980; Watts, 1982), but extended an indeterminate distance *into* space.

disappears if the separation is increased) (-N4, -5G1 FCI). The magnitude of the gravitational force depends on the distance and the relative masses of the two objects (being stronger when close) (I:160).

7.2.4.4 (a) Single-planet probes

While Alex describes a gravitational force acting on the asteroid which is 'towards the centre of the planet', and varies with distance, she does not understand how this causes a change in its path (Figure 7-11).

Figure 7-11: Alex: direction of gravitational force in various part of the orbit.



She is uncertain about which physical quantities might be used to describe the motion, and does not make use of them in her descriptions. In particular, her understanding of the nature of gravitational force is problematic, arguing that it is created between objects when they are '*brought close together*', and yet that '*it always exists*' (I:183) — a 'point-to-point' gravity model that is the antithesis of a field-based model[39]:

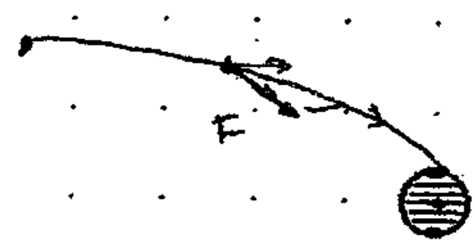
Int: So where do we find gravity in that picture? (Figure 7-11)
Stu: It's described as a force which is created when 2 objects are brought relatively close to each other. It always exists.

This indicates fundamental confusion about gravity — its nature and effects (-5G1, -N2) — in contradiction to her excellent score in the Gravity section of the FCI[40].

39. as opposed to a field model.

In Figure 7-12, she explains that 'The force vector is larger than the one of the momentum, so it changes the path' (1:99), showing confusion about the nature of force and momentum, and what causes the asteroid's changing motion.

Figure 7-12: Alex: momentum vector (horizontal) and gravitational force on the asteroid.



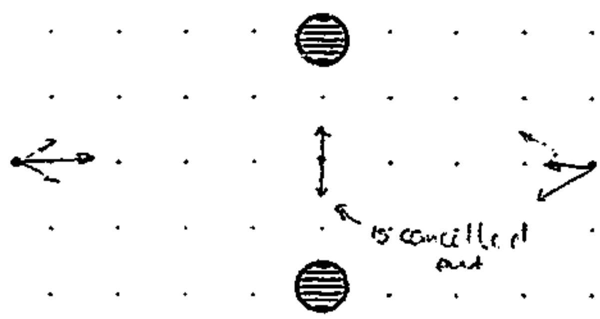
Stu: Um, as the asteroid passes by, there is a direction of force towards the planet … which is always going towards the centre of the planet.
Int: Ok, so why does the path curve?
Stu: Because it is pulling the asteroid towards it sort of.
Int: And what quantities would you use to describe that interaction?
Stu: Quantities?
Int: What physical quantities …
Stu: What do you mean like centripetal force, acceleration whatever?
Int: Whatever…
Stu: Um… I'm not sure.

7.2.4.4 (b) Dual-planet probes

Alex correctly predicts the oscillatory motion, and explains its origins in an 'equal gravitational force' (1:189) arising from each planet (as above) with the vertical components cancelling (Figure 7-13), and subsequently determines that the oscillation is a result of the unique geometry of the probe.

40. Table 7-13 on page 274

Figure 7-13: Alex: vector-based explanation of oscillating motion.



The deflections and orbital motion depicted in the two subsequent probes in this set are explained in terms of the asteroid moving in and out of the gravitational influence (as described above) of each planet (l:223).

7.2.4.4 (c) Multi-asteroid probes

Alex determines that the intra-asteroid interactions affect their trajectory. She does not identify that each asteroid has a different gravitational force on it from the planet and is on a slightly different trajectory. For example, in the case of probe G7:

Int: What can you tell me about the motion, and the reasons for the motion?
Stu: They are getting acted on by the same force, just each in their different positions. So if you were to treat each one in a separate, isolated case, they still behave the same way that you would expect. The difference is that they are still interacting on each other, but the interaction um … is different for the one at the front and the one at the end. (l:265)

While she fails to identify the different magnitude of gravitational force acting on each from the planet by virtue of their varying distances from it, arguing instead (l:274) that:

> They are getting acted on by the same force, just each in their different positions.

in subsequent probes, however, she notes that (e.g., l:313):

> The ones closest to the planet will have a greater… curving effect … I don't know…the planet will …attract them more than the ones further out.

In all of these probes, she persists with her point-to-point gravity model (i.e., as opposed to a field representation) (cf. Section 7.2.4.4 (a)):

Int: And so the gravity in this place still only exists between the individual objects?
Stu: Yeah!

7.2.4.5 Vector probes

While Alex was able to describe what was happening in the probes, and what the vectors were representing, their use did not help Alex to better understand the contexts, nor to provide further insight, nor illuminate further issues in her understandings of gravity and the NFC.

7.2.5 Jim

Jim is undertaking major studies in both Biology and Mathematics, and a sub-major study in Physics. Jim's self-assessment of his knowledge of Physics (in general), and of the area of Mechanics in particular, were both 'average'. His physics background is considered to be normal, with three years of studies in Physics completed (Table A-6 on page 4).

7.2.5.1 FCI questions

The FCI data (Table 7-15) indicate that Jim has a poor understanding of the NFC. His understanding of gravity (Table 7-16) (as measured by the FCI) is also poor. Obvious difficulties with all categories suggest that he will have significant difficulties with all of the probes. Consistent with his overall weakness with the NFC, his FCI-predicted misconceptions (Table 7-17) indicate that he holds a range of potential misconceptions related to impetus (-N1), 'resistance' (possible Aristotelian models), and action/reaction pairs (-N3).

Table 7-15: Jim - FCI results by category.

FCI category	0 K	1 N1	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	3	4	2	0	1	4	33%
Percentage	50%	50%	50%	0%	25%	25%	

Table 7-16: Jim - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	2	0	1
Percentage	33%	0%	50%

Table 7-17: Jim - predicted misconception areas[a] (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	**K1**	**K2**	**K3**				
	×	×	×				
1. Impetus	**I1**	**I2**	**I3**	**I4**	**I5**		
	✓	×	✓	✓•	×		
2. Active Force	**AF1**	**AF2**	**AF3**	**AF4**	**AF5**	**AF6**	AF7
	✓•	×	×	✓•	×	×	×
3. Action/Reaction pairs	**AR1**	**AR2**					
	✓	✓					
4. Concatenation of influences	**CI1**	**CI2**	**CI3**				
	✓•	×	✓				
5. Other influences on motion	**CF**	**OB**					
	×	×					
5.1 Resistance	**R1**	**R2**	**R3**				
	✓	✓	×				
5.2 Gravity	**G1**	**G2**	**G3**	**G4**	**G5**		
	×	×	✓•	×	×		

a. A '•' in a cell means that only one of a number of same-category misconception indicators was chosen.

7.2.5.2 Introductory questions

Jim demonstrates correct understandings of N1 (+N1.1, +N1.2), but does not articulate a causal model. He refers to, but does not use Newtonian arguments or explanations here (NΘ), and does not adequately explain his notions of gravity.

7.2.5.2 (a) Gravity

Int:	What do you think of when you hear the word 'gravity'?	
Stu:	Attraction between 2 bodies I suppose, or think of Newton's laws – gravity between planets.	s+/d- +5G1 (FCI) No causal model.
Int:	What do you think of when you think of gravity?	
Stu:	Ah, a force.	s+/d- No causal model.

Int:	What's the best example you can give of gravity?	
Stu:	Ah an apple falling out of a tree	cf. Joanna (p.248)
Int:	And why is that an example of gravity?	
Stu:	Because it falls to Earth.	s+/d-

Int:	How do you know when and where it's present?	s-/d- only provides contextual criteria for presence - no reason given.
Stu:	Everywhere! On Earth I guess we know it's present when we are walking along the ground and staying there.	s+/d- ()
Int:	How does that tell you it's present?	
Stu:	Cause, cause we have weight.	s-/d- How? (+N2 , -N4?)
Int:	Where does the weight come from?	-5G1 FCI/+G2 FCIM Gravity intrinsic to mass? (cf. force between masses).
Stu:	From the mass of our body…	

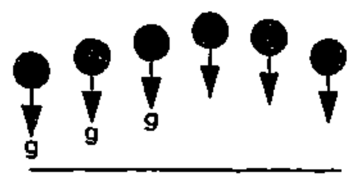
7.2.5.2 (b) Projectile probe

Despite his weakness on the FCI, Jim provides correct responses to this probe:

Int:	What does gravity do to the basketball?	
Stu:	The gravity is making the basketball come back down. If there was no gravity, it would just keep going up.	s+/d- Identifies effect of gravity on the ball +N1.1, +N1.2 (FCI)
Int:	In which direction?	
Stu:	In the direction it was thrown.	
Int:	In a straight line you mean?	+N1.1, +N1.2 (FCI)
Stu:	Well, yeah. Or it could curve up. <as in the probe>	+5G3? (FCI)
Int:	Which way would the ball go if there was no gravity?	
Stu:	If there was no gravity, it would keep going straight!	+N1.1, + N1.2 (FCI)

In Figure 7-14, Jim argues for a constant 'action' of gravity, but whether this means a force, acceleration, or a movement, is unclear.

Figure 7-14: Jim's projectile probe diagram. 'g' represents the 'action' of gravity



7.2.5.2 (c) Summary

Despite his FCI-predicted weakness with the NFC, Jim clearly understands N1 and the action of gravity on the basketball. His responses are not in explicit Newtonian terms (N0), and are generally not definitive statements (d-) about the concepts under examination.

7.2.5.3 Video Probes

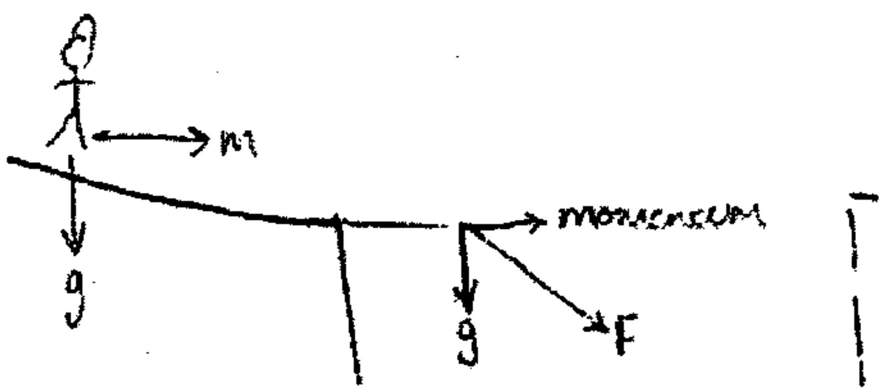
In these probes, Jim's responses are in accord with the FCI predictions. Jim identifies the incorrect projectile motion (+5G3 FCI), but argues that projectile motion is a result of the vector addition of two different quantities — momentum and gravity (-K0.3; -5G3 FCI), which perhaps implies an active force model (motion implies active force - AF2 FCIM).

7.2.5.3 (a) Homer's leap

Jim correctly identifies the incorrect projectile motion, but also states that the skate board would have not stayed at his feet, but would have followed a different (presumably lower) trajectory — an argument that seems in contradiction to his responses to the following probe. He explains projectile motion (Figure 7-15) as being due to the vector addition of momentum and gravity[41] (I:141):

Int: Do you want to explain your diagram please? (Figure 7-15)
Stu: Ah, well we've got… Just left the cliff. Gravity going straight down…towards Earth… Momentum keeps going with inertia… from when he leaves the cliff, and just the force would be the…, probably would be … closer to…
Int: Is that meant to be some kind of vector sum of that, or what?
Stu: Yeah. Yeah, so it would be…. The force would be taking him on the trajectory of the flight...

Figure 7-15: Jim: Explanation of cause of projectile motion.



There is no explanation for Homer's sudden fall (1:150):

Int: What do you think happens at that last point where he suddenly goes down'?
Stu: That's where the cartoon takes… takes over.

7.2.5.3 (b) Road runner probes

Jim identifies the incorrect projectile path in the first video clip (Section 6.4.3.3 a.(2) on page 215), noting that 'a component of gravity' should have pulled him down in an arc' (1:62), but does not articulate this in Newtonian terms. In the second video clip (Section 6.4.3.3 (b) on page 216) he describes the rotation in falling as an animistic 'cat-like force', but also argues (incorrectly) that perhaps having more weight in his boots would also produce a rotation (+AR1 FCIM) (1:74):

41. two different quantities that cannot be added together.

Int: What would need to happen?
Stu: Maybe um ... maybe um more weight in his feet to pull that down quicker compared to...
Int: So you think the weight in the feet would help stabilise that?
Stu: Yes.

He uses the argument that 'heavy falls faster' in a number of places in these probes to explain why particular objects would fall at different rates than those depicted, or why they could not remain stationary as things fell around them (+AR1 FCIM).

7.2.5.4 Planetary computer probes

Jim displays a superficial understanding of the action of gravity in these contexts, being able to successfully predict many of the events depicted. However, he rarely uses Newtonian arguments, and his explanations demonstrate considerable confusion about the nature (and relationship) of gravitational force and field.

7.2.5.4 (a) Single-planet probes

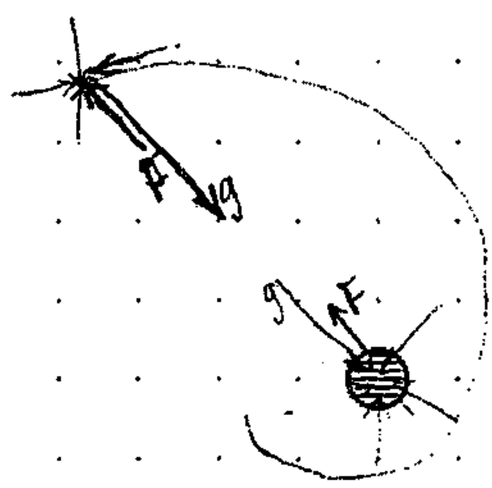
Jim correctly predicts that gravity will deflect the passing asteroid (I:176), and describes a radially-directed field model (as opposed to a point-to-point model) of gravity (I:198), and argues that the 'local' gravity on the surface of each will depend on its mass (I:180), but does not discriminate between the local gravity and the magnitude of the gravitational force between them (i.e., according to N4).

Stu: There is greater gravity on the planet, because the mass of that is bigger ... than the asteroid, so there would be less gravity on the asteroid, ... on the surface of the asteroid.... there would be a gravitational force attracting the two bodies... to keep the asteroid in an orbit.
Int: So where is the gravity on the asteroid and on the planet?
Stu: Yeah, um, between them. Between them.
Int: Anywhere else?
Stu: All around the planet and the asteroid, and between both.
Int: How would you describe that ... a field?
Stu: Yeah, gravity field.

Int: What would it look like if we could see it?
Stu: Towards the centre of the planet, and all around it, and the asteroid...
Int: What can you say about forces in that environment as well as gravity?
Stu: Well there is an attractive force between them.

However, Jim seems confused about the action of gravity when asked to represent it in a diagram (Figure 7-16), where both force *and* gravity vectors are drawn. In Figure 7-16, it is noteworthy that both gravity vectors are directed towards the planet, and both force vectors towards the asteroid. Presumably this confusion arises, from a failure to discriminate between local and intra-planetary gravitational forces, or because force and gravity are viewed as different entities, or perhaps even as a misunderstood action-reaction situation.

Figure 7-16: Jim: action of gravity between a planet and an asteroid.



Further concept and action confusion is evident in probe G2 when an apparent active force model (+AF2 FCIM) is used to explain why slower or closer asteroids are more likely to be captured by the planet:

Int: Why do you think that happened? Stu: Ah cause it was closer. The force became stronger as the distance between the 2 decreased, the force - gravitational pull - of the big planet increased.	(Slow, nearby, asteroid impacts on planet) s+/d- -N4 (no causal relationship mentioned).
Int: And what if it had been going faster perhaps? Stu: Ah, … I think it would just happen faster.	
Int: Want to explain that? Stu: So the increased speed of the asteroid … um… Int: It's hard to explain?	(Fast asteroid at same distance misses planet)
Stu: Yeah its sort of… it took it past… the planet because… because there was a force which was great enough to miss the planet, and then… stay…or not crash into it… Ah…	Active force model? (+AF4)
Int: So what do you think made it go past? Stu: The acceleration … um… component of the asteroid.	Active force model? (+AF5)

7.2.5.4 (b) Dual-planet probes

Jim appears to understand the action of gravity in these probes:

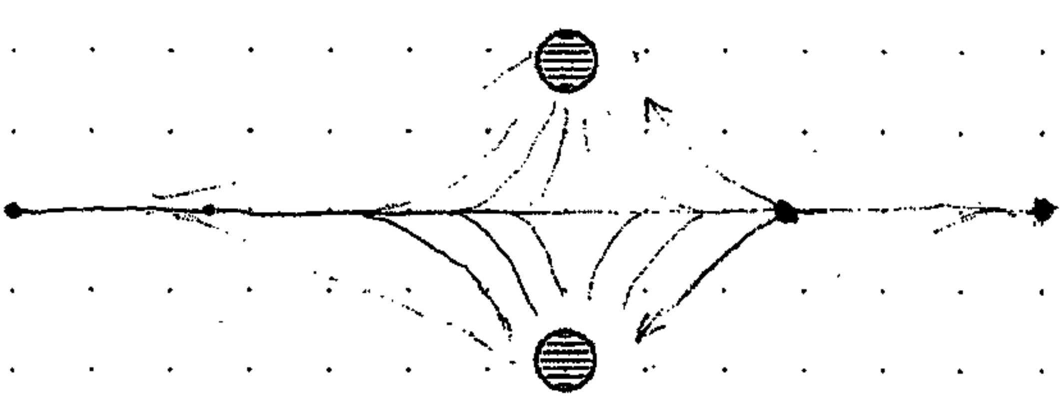
> The gravity force of the 2 planets are keeping it in a straight line orbit, and attracting it back towards the planets. (1:264)

However, Jim explains this with his field model of gravity (as in Figure 7-17), confusing 'lines of gravitational force' with the equipotential surfaces[42] of the gravitational *field strength* (i.e., when he refers to the lines in Figure 7-17 as being 'lines of gravitational *field*', which would be perpendicular to those in the diagram). It is not clear what the term 'lines of force' means (i.e., in relation to his field model), particularly as they are curved, rather than being directed towards the centre of each planet. He also argues that gravity stops acting at the end — which is contradictory to his comments about the 'gravity force' acting on the asteroid.

42. i.e. 'contours' mapping regions of equal gravitational field strength.

Int:	So what are these curves you are drawing here? (I:271)	(refers to Figure 7-17)
Stu:	These could be the lines of force that are acting on it... the gravity of the planets.	Is this an analogy, or do they imply problems with non-contact forces? -5G1 (FCI).
Int:	So they are lines of force, or are they representing lines of gravitational field?	
Stu:	... lines of gravitational field from the planet that are attracting the asteroid. And they get weaker as the distance increases... and as the asteroid is getting closer, because of this gravitational field, is getting quicker through ...the middle... and it slows down to a stop when the... when the gravity stops acting.	-s/-d confuses field with force? local vs. interplanetary force confusion? -5G1 (FCI)
Int:	When the gravity stops acting at the end here?	
Stu:	Well it's... it's... yeah, it loses,... it's losing momentum as it get towards the outer section of the gravitational field.	
Int:	So does this gravitational field stop around here you mean or what does it do?	
Stu:	I think it keeps going on further.	
Int:	You said the object stops because it loses momentum.	Contradicts statement above. Field-force issue? Changes gravitational *force* between them. -5G1
Stu:	Yeah, so the mass of it sort of, is um... changing the strength of the gravitational field.	

Figure 7-17: Jim: action of gravity between the two planets and the asteroid.



Subsequently (I:317), he again argues that the gravitational field has finite boundaries, but apparently this may be a semantic, as opposed to conceptual, issue:

Stu: Ok, so the initial... yeah, the gravitational force from the bottom planet didn't affect it as much as I thought it would. It remained on its course until it got within the ...gravitational field of the top planet.
Int: Now when you say it got within the gravitational field of the top planet?
Stu: Well it was stronger from the top planet than the bottom
Int: The field either stops somewhere or is it continuous?
Stu: Its continuous but with the distance,... it varies with the distance the asteroid is away from it.

7.2.5.4 (c) Multi-asteroid probes

Jim uses similar arguments to those above in explaining the motion in these probes. He identified the intra-asteroid interactions, and also predicted that asteroids closer to planets would be those attracted most strongly to them. He was able to use these ideas to successfully predict or explain the motion in these probes, but not in precise Newtonian terms.

7.2.5.5 Vector probes

Jim states that the existence of a radially directed gravitational force is due to a centripetal acceleration, but does not articulate it further in Newtonian terms. He was unable to clearly articulate[43] why the asteroid's velocity vector was continuously changing direction while orbiting the planet (1:441):

Int: Can you explain this velocity vector diagram?
Stu: It's a force. That force hasn't changed, and… but the gravitational force has affected the direction of it.
Int: The gravitational force has affected the direction of the …
Stu: Velocity.
Int: The velocity vector. How?
Stu: It's pulling it.
Int: So its basically pulling the velocity vector around?
Stu: Yeah.

7.2.6 Joe

Joe is undertaking major studies in both Biology and Mathematics, and a sub-major study in Physics. Joe's self-assessment of his knowledge of Physics (in general), was 'average', and of the area of Mechanics in particular, was 'good'. Because of interruptions to his studies, Joe has not followed a normal course enrolment pattern,

43. in Newtonian terms.

and only after completing the majority of his other course subjects is he able to complete the required sequence of Biology units (Table A-7 on page 5). Joe's physics background, however, is considered to be normal, with three years of studies in Physics completed.

7.2.6.1 FCI questions

The FCI data (Table 7-18) indicate that Joe has a poor understanding of the NFC — in contrast to his self-assessment. His understanding of gravity (Table 7-19) (as measured by the FCI) is also poor — obvious difficulties with all categories suggest that he will have significant problems with all of the probes. Consistent with his overall weakness with the NFC, his FCI-predicted misconceptions (Table 7-19) indicate that he holds a wide range of potential misconceptions across the dynamics categories, particularly in regard to impetus (I1, I2), active force (AF4), and action-reaction pairs (AR1).

Table 7-18: Joe - FCI results by category.

FCI category	0 K	1 N1	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	1	4	1	1	1	5	31%
Percentage	17%	50%	25%	25%	25%	31%	

Table 7-19: Joe - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	2	0	1
Percentage	33%	0%	50%

Table 7-20: Joe - predicted misconception areas[a] (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	K1	K2	K3				
	×	×	×				
1. Impetus	I1	I2	I3	I4	I5		
	✓	✓•	✓	✓•	×		
2. Active Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7
	✓•	×	×	✓	×	✓•	×
3. Action/Reaction pairs	AR1	AR2					
	✓	✓•					
4. Concatenation of influences	CI1	CI2	CI3				
	×	×	✓•				
5. Other influences on motion	CF	OB					
	×	×					
5.1 Resistance	R1	R2	R3				
	✓•	×	×				
5.2 Gravity	G1	G2	G3	G4	G5		
	×	×	✓•	×	×		

a. A '•' in a cell means that only one of a number of same-category misconception indicators was chosen.

7.2.6.2 Introductory questions

Consistent with his FCI score, Joe demonstrates fundamental confusion about basic Newtonian and gravity concepts, describing an Earth-based model of gravity that is caused by the Earth spinning, and which stops at the edge of the atmosphere (-N4, -5G1 FCI).

7.2.6.2 (a) Gravity

Int: What is gravity?
Stu: Oh it's the force acted or gravitational force or acting towards the Earth's surface or the atmosphere.
Int: What causes gravity?
Stu: Ah, gravitational force of the Earth as it's spinning around, sort of.
Int: OK what do you mean when it's spinning around?
Stu: Just ah, sort of, just ... I don't know!

s-/d-, -5G1 (FCI) - gravity acts towards Earth and atmosphere? -5G1 (FCI) Relates gravitational force to Earth's rotation. (cf. Nelson, 1991)? (Stead & Osborne, 1980) Possible confusion with centripetal force. Confusion evident as to origin. (N0)

Int: And how do you know when and if gravity is present?
Stu: Um, oh you can sort of feel it, … being attracted in certain ways, like weightlessness … it's not occurring… or something like centripetal force would overcome gravitational force from the Earth.
Int: OK and so how would you know when it's present?
Stu: Um. If you drop something and it falls.
Int: And where do you find gravity?
Stu: Everywhere.
Int: Everywhere? Why?
Stu: Because it's part of our lives. Everything is affected by it.
Int: OK. So is it only on the Earth?
Stu: When you say everywhere, what do you mean? Oh, on the Earth, yeah. Outside our atmosphere and whatever in space it's not … we don't have it. So it is something to do with the Earth.

s-/d-
-N2 gravity acts but zero nett force.
(prob. meaning "centrifugal" non-Newtonian notion) (cf. Williams, 1988) -5G1 (FCI)

-5G1 Gravity stops at the edge of the atmosphere (cf. Stead & Osborne, 1980; Watts, 1982,p.118) -

NB.Compare with responses to planetary probes in Section 7.2.6.4

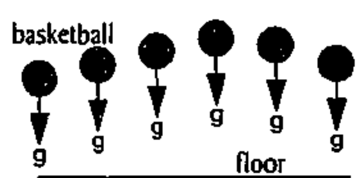
7.2.6.2 (b) Projectile probe

Int: What does gravity do to the basketball?
Stu: It attracts it back towards the Earth, towards the floor.
Int: And so does that explain the curve of the ball?
Stu: Well the person throwing the ball is working against gravity, and once that work is overcome by gravity, at the top of its curve, and it starts… starts to curve back.
Int: Show me how gravity acts on the ball.
Stu: It's on all of them!

s+/d-
s-/d- Lack of precision in usage. Implies 'gravity' (a stand alone 'entity?) uses up 'the work' rather than the Earth doing work on the ball. Poor explanation of work/energy concepts.

Joe's diagram (Figure 7-18) is identical to Jim's (Figure 7-14), apart from minor labelling differences. Here, 'g' represents the force of gravity.

Figure 7-18: Joe's projectile probe diagram.



7.2.6.2 (c) Summary

Joe appears to have no Newtonian understandings of gravity (N0, -5G1 FCI), believing that gravity is Earth-bound (-N4), caused by its rotation (-N4), and stops at the edge of the atmosphere (-N4) (cf. Nelson, 1991; Stead & Osborne, 1980; Watts, 1982; Williams, 1988).

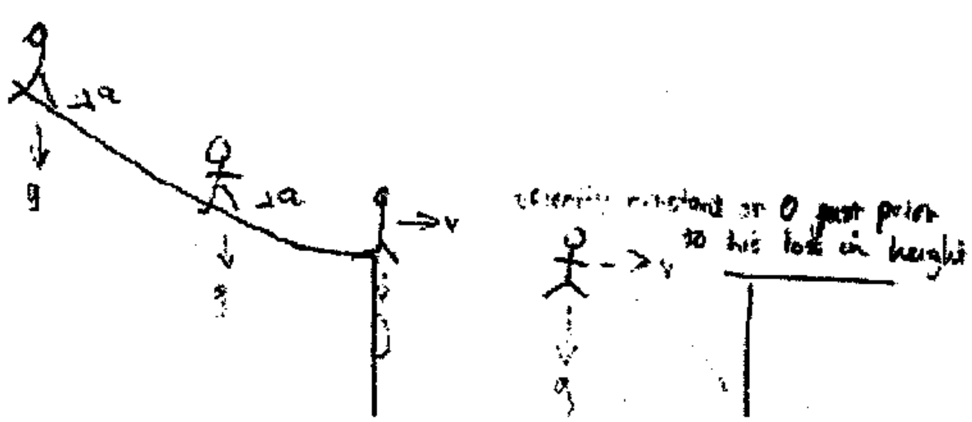
7.2.6.3 Video Probes

Joe demonstrates some knowledge of the basic principles of Newtonian mechanics that are relevant here, but cannot articulate these clearly, appears confused about some concepts, and argues inconsistently about the effect of gravity on falling objects.

7.2.6.3 (a) Homer's leap

Joe apparently understands the motion down the incline, arguing that at the edge of the cliff, Homer should have a vertical component of velocity[44] that, along with gravity, would result in his fall following a 'gradual' curve (+K0.3 FCI) (I:176), and identifies where gravity would be acting (Figure 7-19). These improved understandings (i.e., to those demonstrated above) may be due to this probe portraying a more familiar context (projectile motion and free fall).

Figure 7-19: Joe: Forces on Homer during motion, showing the predicted trajectory.



Joe argues that Homer's (horizontal) velocity prior to fall could be either constant, or perhaps zero (perhaps symptomatic of a partial impetus view), and that gravitational acceleration 'suddenly picks up' (I:198) where he suddenly falls

44. The actual angle (up, down, or horizontal) at which he leaves the cliff edge cannot readily be estimated.

(possibly +I3; +AF7 FCIM). No reason is given for this phenomenon, which is contradictory to his previous explanation.

7.2.6.3 (b) Road runner probes

Joe argues for a 'sort of' *parabolic* curve in probe 1, because '...he's got forward momentum and then gravity acts on him[45].' (l:49), also stating that 'He's got a vertical and horizontal force on him.' (l:51), showing probable confusion about the relationship between force and momentum. Similarly, Joe notes that all of the falling objects depicted in the subsequent probes (in this series) would start falling at the same time, but at a rate that depends on their weight (l:88) (+5G3 FCIM), and that their motion is abnormal — '...just ridiculous, totally ridiculous' (l:101). In contradiction, he subsequently states that falling objects would all fall at the same rate (l:103).

7.2.6.4 Planetary computer probes

Joe notes that planets have a gravitational field around them that gradually diminishes with distance (l:500), and that gravitational force between two objects is directed along the line between them (l:482), but misunderstands N4 (as below).

7.2.6.4 (a) Single-planet probes

Joe states that a 'parabolic movement - curved path' is indicative of gravity (l:347). He demonstrates confusion with N4 when changing the masses in trying to make the asteroid orbit the planet (l:448):

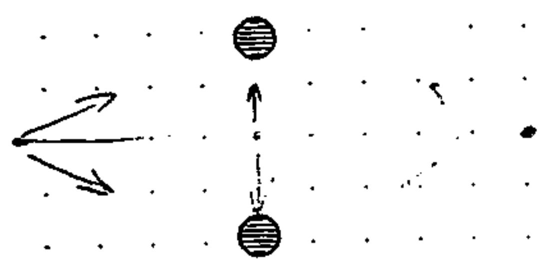
45. i.e., as he moves away from the cliff face.

Int: So what are you going to do to try to make it orbit now?
Stu: Try and increase the mass of the ... that shouldn't change it ... I'm lost!
Int: Shouldn't change the gravity?
Stu: <pause>. But that ... changing the mass of the planet won't change the gravitational pull it will have on the asteroid.
Int: So if you don't think it will, what else might you change?
Stu: The mass of the asteroid...because the gravity from the planet... will affect the asteroid in a differing way ... from ways if its mass is different ... so ...

7.2.6.4 (b) Dual-planet probes

As in Figure 7-20, Joe correctly explains the forces acting on the asteroid.

Figure 7-20: Joe: Gravitational pull acting on the asteroid.



However, in the subsequent probes in this series, he argues that the greater attraction from the planet closest to the asteroid is due to the asteroid going '...beyond the lower planet's gravitational pull' (1:527). This is inconsistent with his statements about fields (above).

7.2.6.4 (c) Multi-asteroid probes

Joe does not detect the intra-asteroid forces. In probe 7, he argues that the fan-out effect is because the asteroids are accelerating, but does not articulate what this really means. He correctly predicts the initial motion in probe 8, but is surprised as the asteroids are pulled back to the planet by its gravity. He correctly explains their curvature as resulting from the changing gravitational forces on the asteroids as they move, which varies their distance from the planet, and hence the force on them.

7.2.7 James

James is undertaking major studies in Biology and Sociology, and a sub-major study in Physics. His self-assessment of his knowledge of both Physics (in general), and the area of Mechanics in particular, were both 'average'. His physics background is considered to be normal, with three years of studies in both Physics and Biology completed (Table A-8 on page 5).

7.2.7.1 FCI questions

The FCI data (Table 7-21) indicate that James has moderate understandings of the NFC. His understanding of gravity (Table 7-22) (as measured by the FCI) is also moderate, with apparent difficulty in understanding the origin or nature of parabolic projectile paths — which is a significant component of most of the probes. Difficulties with kinematics, N2 and 'kinds of forces' suggest that he may have problems with force-mass relationships (-N2) and with the 'effects' of force on objects (-N2) depicted in the probes. Consistent with his moderate understanding of the NFC, his FCI-predicted misconceptions (Table 7-23) indicate that he holds a number of potential misconceptions related to 'active force', impetus, effects of multiple forces (CI_1, CI_2), and resistance (possible Aristotelian models), all of which may make it difficult for him to articulate correct answers to the probes.

Table 7-21: James - FCI results by category.

FCI category	0 K	1 N1	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	2	5	1	4	3	8	55%
Percentage	33%	63%	25%	100%	75%	50%	

Table 7-22: James - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	3	2	0
Percentage	50%	100%	0%

Table 7-23: James - predicted misconception areas[a] (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	K1	K2	K3				
	×	×	✓				
1. Impetus	I1	I2	I3	I4	I5		
	✓•	×	✓	×	×		
2. Active Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7
	✓	✓	×	×	✓	×	✓•
3. Action/Reaction pairs	AR1	AR2					
	×	×					
4. Concatenation of influences	CI1	CI2	CI3				
	×	✓•	✓•				
5. Other influences on motion	CF	OB					
	×	×					
5.1 Resistance	R1	R2	R3				
	✓•	✓•	×				
5.2 Gravity	G1	G2	G3	G4	G5		
	×	×	×	✓•	×		

a. A '•' in a cell means that only one of a number of same-category misconception indicators was chosen.

7.2.7.2 Introductory questions

James describes gravitational force as an interaction between two masses (+5G1/+N4), uses 'falling' as opposed to 'accelerating' in describing gravitationally induced motion, and demonstrates apparent confusion about its pervasiveness throughout the Universe (-N4).

7.2.7.2 (a) Gravity

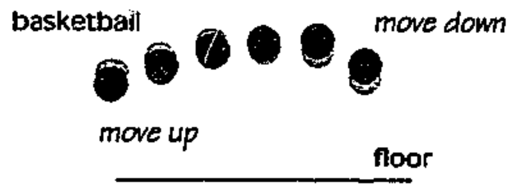
Int: What do you think of when you hear the word 'gravity'?	
Stu: Force, a force of attraction that exists … straight away I think planets … there's an attraction between them and I suppose falling objects.	s+/d+ +5G1 (FCI)
Int: Why?	
Stu: Because it's the force of attraction between 2 masses, and … it's proportional to the distance away those masses are. No matter how far away, there will always be a force of attraction between those 2 masses.	-N4: relationship not fully *defined*. *s+/d-* +5G1 (FCI) *Correctly emphasises the gravitational interaction* ***between*** *masses rather than as an attribute of mass (cf. Arons, 1990, p.70; Galili, 1993)*
Int: What's your best example of gravity?	
Stu: If a student said that to me, I would have a tennis ball or something in my hand and drop it, and ask why it fell to the ground.	*s+/d- imprecise - use of 'fall' as opposed to 'accelerate'*
Int: What would you say?	
Stu: Well because you have 1 mass here and another mass - the Earth, and the attraction between the masses caused the … object to fall.	+5G1(FCI)
Int: Where do you find gravity?	
Stu: You would find it anywhere almost in the Universe…	s-/d- "Almost"? -5G1 FCI

7.2.7.2 (b) Projectile probe

Int: Do you think it's a realistic diagram?	
Stu: Yeah I'd say it was pretty right because the further it gets, … its horizontal speed will decrease.	The rapid fall of ball (*past apogee*) is *due to reduced* V_X -KΘ.3/(FCI) No *mention of vertical acceleration.*
Int: Why is that?	
Stu: Air resistance I would say. It's working against him.	
Int: Do you have a problem with it?	+5F1 (FCI) *Correct use, but not realistic in the context as depicted.*
Stu: Yeah it's a bit … I am not quite sure as to how far they are dropping down. If this ball here is the same as this one, then that should… and that's the top of its flight, then that should have dropped down to the same…	-5G3 (FCI) *Detects incorrect projectile path, but not stated as a parabola.*

James simply annotated the diagram in his interview booklet, stating that, as above, 'parts of the curve were wrongly drawn and needed to be moved up or down.', recognizing, but not formally, that the expected parabola would be symmetrical.

Figure 7-21: James' projectile probe diagram.



7.2.7.2 (c) Summary

In general accordance with his FCI scores, James is able to describe some aspects of gravity, but is unable to articulate them in precise Newtonian terms.

7.2.7.3 Video Probes

James determines that gravity is constantly acting vertically, causing the roll down the slope and the incorrect trajectory. The sudden fall is wrong, as the trajectory should be a gradual[46] curve, resulting from both gravity and air resistance (as in the previous probes) but is confused about how air resistance acts to do this.

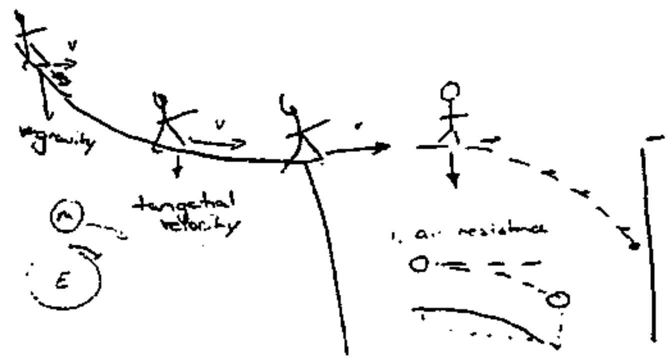
7.2.7.3 (a) Homer's leap

James identifies problems with the trajectory (but does not refer to a parabola -5G3 FCI), suggesting that it should follow a more gradual drop down (1:254) as in Figure 7-22, but is uncertain as to why that should happen:

Stu: But the way I see it is ...he got across and then he lost.... He was going ok then just at one point he dropped ...just went down. That just wouldn't happen. It would be more of a gradual ...
Int: Why wouldn't it happen? Why do you think it is wrong?
Stu: Cause he um ... ...well why wouldn't it happen. I don't think I can answer that.

46. n.b., no mention of a parabola.

Figure 7-22: James: Explanatory diagram of Homer's leap.



As in Figure 7-22, gravity acts vertically, and James struggles to explain how it causes Homer to roll down the slope due to a tangential velocity (i.e., along the slope), suggesting problems with vector resolution. He does not use vector concepts in explaining its origin:

Int: And where does the velocity come from? Stu: Gravity is applying a downward force … Ok, and it's the shape of the …hill. He … can't go down. He is going to be forced along the shape of the hill, but the gravity is always acting on him, …pulling him down. So you've still got the gravity and then you end up with an increase … in your velocity because the gravity has had longer to work…ah. Longer to work on him. Int: The gravity is acting vertically down isn't it? Stu: Yeah.	(see Figure 7-22). s-/d- -KO.5 (FCI) +KO.3? (FCIM). *Unable to explain motion on an inclined plane in terms of vector quantities and resolution of vectors.* Poss. -N3 (FCI) *Usage not clear - poor use of terms:* possibly refers to *time taken,* but 'work' implies *gravitational work* done on Homer that leads to an increase in KE.

Air resistance is considered to be responsible for the curvature, but when probed, James provides an orbital analogy in an attempt to explain what would happen in the absence of air resistance (which he does not achieve), juxtaposing arguments from linear and rotational frames of reference:

Int: If there were no air resistance, how would the path be different? Stu: Well the situation is sort of like the Earth & Moon, right, where the moon continually falls around the Earth. But it's got to happen, it's got to have … tangential velocity is got to be great enough so it covers the curve of the Earth. Int: How do you mean? Stu: Like the slope of the Earth. The moon's got to cover enough distance in 1 sec. That it, when it falls… it's falling into the slope around the Earth. Int: Ok I see so it's exactly the same height above the Earth there and there? Stu: Yeah. It's like,… can't remember exactly what it is …there's the slope … and it goes around. The effective gravity um … is the same but it keeps it circling. So because his tangential velocity isn't large enough … for that to happen, he would fall into the Earth. So I guess the same… I mean. It would be the same without air resistance.	Difficult analogy to use because it relates events in one frame of reference to another. In this case, James does not appear to comprehend that Homer is undergoing rectilinear motion above what is essentially a small section of a plane surface, whereas in the planetary situation, the Moon is falling around a sphere (i.e. Earth). Little apparent realisation of scale and geometry issues. s-/d- Radial fall -> *decreased* centripetal force (of gravity). Homer's due to 'vertical' action of gravity (i.e., frame of reference issue)

James comments on the 'Ollie', arguing that it is possible:

Int: Think he could do that? Stu: That's actually puzzled me. … I can't see why not. Int: So he and the skate board are flying across and he does a jump up… Stu: Yeah as long as they are both moving with the same horizontal velocity, … him jumping up… yeah I can't see why not. I keep seeing … in space… you know what do you call it – in a space ship. If you are going along in a space shuttle, that's the same sort of principle… Int: So inside a shuttle, you jump off the floor and it's Ok? Stu: Yeah, cause you are moving along, so I would say that is possible.	-N2.1, -N3.1 (FCI) Equal & opposite forces on skateboard would cause acceleration of skateboard. Relates situation in 'zero gravity' to free-fall but does not consider relative mass - i.e., shuttle vs. skateboard or if 'internally' vs 'externally' applied impulsive force is significant.

7.2.7.3 (b) Road runner probes

James argues that, because the coyote's body is so short, the stretching effects are improbable because gravity would act equally over it. There is no comment about its rigid or elastic nature. Events in which objects fall at different rates are wrong because 'The objects would all fall at the same rate.' (1:150).

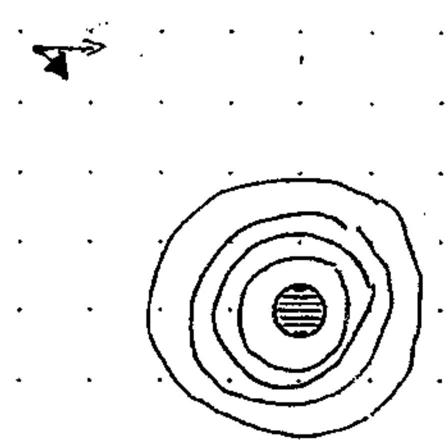
7.2.7.4 Planetary computer probes.

In contradiction to his FCI results, James has a good Newtonian understanding (+N4) in the events depicted, with some confusion evident about the representation of force vectors and fields.

7.2.7.4 (a) Single-planet probes

James describes the nature[47] of, and variation in, the gravitational field strength around a planet in terms of circular field lines ($g=f(r)$) — which he describes as representing 'the (same) amount of force' (see Figure 7-23), and is apparently confused about the relationship between that representation and the direction of gravitational force at a point in the field. He subsequently (Section 7.2.7.4 (b)) demonstrates a clear understanding of N4 (see Figure 7-25).

Figure 7-23: *James: gravitational field around the planet.*



Stu: These are gravitational field lines. Int: So what does that mean? Stu: At… any point in that system there, you have a gravitational force acting on you because of the planet, and these lines represent how much … how large that force of attraction is. Int: What's the arrow represent?	*s+/d+ correct representation and explanation (but should be 'proper' circles).* *s+/d- Correct interpretation, but fails to discriminate between field strength and the force on a mass (such as the asteroid) at a given point in the field.*

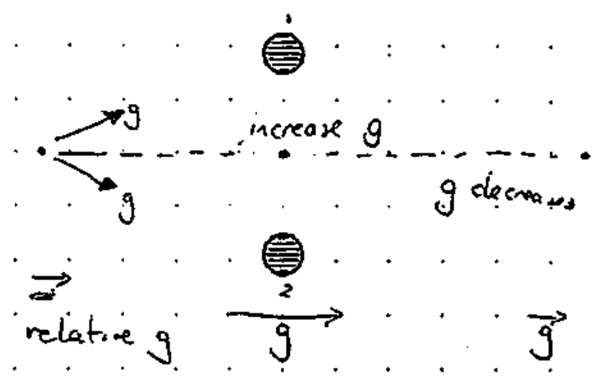
47. i.e., in basic Newtonian terms.

Stu: The arrow represents the force of gravity, or the acceleration ... that it's going to proceed in that way.	
Int: ... the forces go in and the circles go around. What's the relationship?	s+/d+ -N4 - no causal relationship.
Stu: Ok. The circles are just ...... All they represent is the amount of force at that point. They don't represent the direction of the force. The direction of the force is ... Towards the planet ... or asteroid.	

7.2.7.4 (b) Dual-planet probes

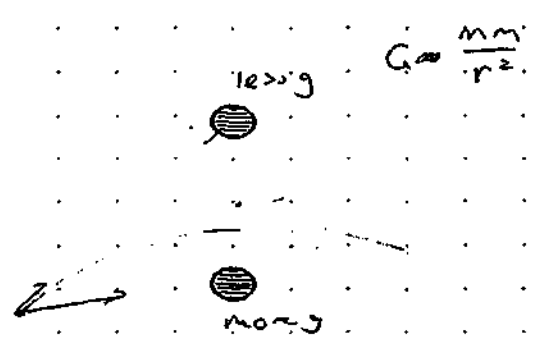
James readily understood the action of gravity in these probes, arguing that it is caused by the varying (but equal) gravitational forces from the planets (Figure 7-24)

Figure 7-24: James: explanation of asteroid oscillations. (note 'g' refers to the total gravitational force on the asteroid.



The effect of the asteroid's relative distance from the planets on its motion was clearly described in terms of N4 (as depicted in Figure 7-25).

Figure 7-25: James: explanation of relative distance on the asteroid's path.



7.2.7.4 (c) Multi-asteroid probes

James identifies the interaction between asteroids as a 'concertina effect' (1:675), and offers two possible explanations for the fan out effect in probe 7 of this series:

Stu: (1:696) The reason they get the concertina effect is… cause when they have started there, this first asteroid is closer <to the planet> so it's got an increase of acceleration, so it will come around and have an increase of speed. I'm talking a bit of bull there! What I was going to say was that because it's closer, it will have an increased initial speed if you will, and they will fling it around, I mean it will increase more …increase ah hang on …so it's starting off from a high initial speed, so when it accelerates it will have a higher speed, and it will end up with enough speed to just fling it around a bit more, whereas these ones a bit further back and start off with a lower initial speed, they don't have, their final speed… they accelerate at the same rate that this one did, but they don't end up with as much as this one did to zoom around.

and:

Int: (1:712) Why does this thin line here spread out into a fatter line?
Stu: I would say it's because the… as they are moving along to this point here, they are all receiving gravitational force from each other, but then the gravitational force of the planet is such that it increases the speed, increasing the distance between each one. It increases the speed of the front one, so it increases the distance between each, so they receive less of the gravitational effect between each asteroid. So they are receiving, I mean they are getting less. And as… I mean …so this front one then shoots off and they have still got a gravitational effect from the front one, and that sort of drags the next one along – a bit out.

The first part of the former, which focuses on the asteroid-planet interaction, is close to being correct, with the closest asteroid having the greatest gravitational attraction to the planet, but James then becomes confused and argues cyclically, forgetting the crucial fact that in this probe, the asteroids all start with the same velocity. The second argument, focusing on the intra-asteroid interaction, is also partly correct, but fails to acknowledge the vastly greater gravitational effect from the planet.

7.2.7.5 Vector probes

While James has little problem in correctly interpreting the events in these probes, the representation of acceleration and velocity vectors during orbital motion (Figure 7-26) caused concern when the velocity vectors appeared to change more rapidly than expected due to a scaling issue in the probe's design. Whether this recognition is due to James believing that N4 would not probably cause such a rapid change in velocity with such small changes in separation, or his possibly being alarmed by its variation in relation to changes in the gravity vector, is unclear (1:927):

Stu: Yes that actually looks longer … ah… what I would expect to happen …is for the small velocity then an increase in velocity. It would reach its largest point here, and then a decrease in velocity… … right around there and a decrease, but if you got a decrease like that …no… that's what I would expect.

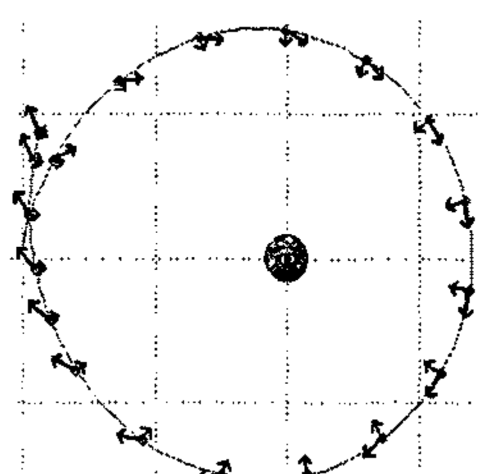
Int: What did you expect?

Stu: What I think we've got now is an increase … slight increase it seems, slight increase … then … a significant increase around there, and that looks like it might be decreasing around there.

Int: So… are you happy with that? Can you explain it? Think it's right or wrong?

Stu: I think the acceleration part is fine… the acceleration part… but I again have doubts on the velocity parts of it.

Figure 7-26: Velocity and acceleration vectors in probe IP3.



7.2.8 Steve

Steve has an unusual enrolment pattern, undertaking a double-major study in Physical Education, and also a major in Physics. Steve's self-assessment of his knowledge of both Physics (in general), and the area of Mechanics in particular, were both 'average'. His physics background is considered to be better than average because of the completion of additional fourth year specialist physics units[48] (Table A-9 on page 5).

7.2.8.1 FCI questions

The FCI data (Table 7-24) indicate that Steve has a moderate understanding of the NFC. His understanding of gravity (Table 7-25) shows probable difficulties in all three categories. Difficulties with N2, N3, superposition, and 'kinds of forces' suggest that he may have problems with force-mass relationships (-N2) and with the 'effects' of force on or between objects (-N2, -N3) depicted in the probes, especially when there are several interacting objects. Consistent with his moderate NFC understandings, his FCI-predicted misconceptions (Table 7-26) indicate that he holds a number of potential misconceptions related to impetus (I_3), active force (AF_6), action-reaction pairs (AR_1, AR_2), concatenation of influence (CI_1-CI_3), and gravity, all of which may make it difficult for him to articulate correct or coherent answers to the probes.

48. see Section 2.6.1 on page 40.

Table 7-24: Steve - FCI results by category.

FCI category	0 K	1 N1	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	4	5	2	0	1	6	43%
Percentage	67%	63%	50%	0%	25%	38%	

Table 7-25: Steve - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	1	1	1
Percentage	17%	50%	50%

Table 7-26: Steve - predicted misconception areas[a] (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	K1	K2	K3				
	×	×	×				
1. Impetus	I1	I2	I3	I4	I5		
	✓•	×	✓	✓•	×		
2. Active Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7
	✓•	×	×	×	×	✓	×
3. Action/Reaction pairs	AR1	AR2					
	✓	✓					
4. Concatenation of influences	CI1	CI2	CI3				
	✓•	✓•	✓•				
5. Other influences on motion	CF	OB					
	×	✓•					
5.1 Resistance	R1	R2	R3				
	×	×	×				
5.2 Gravity	G1	G2	G3	G4	G5		
	✓•	×	✓•	×	×		

a. A '•' in a cell means that only one of a number of same-category misconception indicators was chosen.

7.2.8.2 Introductory questions

Steve determines that falling (as opposed to accelerating) to the Earth's surface is a defining property of gravity (-5G1 FCI) — which does not exist in space (-N4, -5G1 FCI) (Stead & Osborne, 1980) possibly because of the lack of a medium to act through (Watts, 1982)[49], where objects float (rather than fall) (Nelson, 1991). This property can be used to detect the presence or absence of gravity. While explaining N4 correctly (+N4) (i.e, the formula), he does not explain why it apparently stops acting in space. Gravity is selective in its action (cf. Watts, 1982)[50], apparently speed dependent, with a greater effect on slow objects (cf. Watts, 1982)[51](-5G1 FCI).

7.2.8.2 (a) Gravity

Int:	What do you think of when you hear the word 'gravity'?	
Stu:	Well free falling objects, 9.8 m/s^2 gravitational acceleration, that sort of thing. Um ... gravitational attraction, forces of the Earth as in force = GM_1M_2/r^2 where G is the gravitational constant, M_1 & M_2 is the mass of the Earth for instance and M_2 can be the mass of the object like a satellite and r^2 is the radius.	*s+/d-* +N4 (*verbal slip? - equation articulated correctly but subsequently uses r^2 for radius*) *s-/d-* -5G1 (no mention of attraction *between* masses: possibly implied but not stated)
Int:	Do you think of it as a force, or a field or what?	
Stu:	I think of it as a force, gravitational attraction force.	
Int:	What's your best example of gravity?	
Stu:	Probably just dropping a free-falling object at a certain height knowing that it must come to the Earth's surface due the gravitational ... gravity sort of thing.	*s+/d-* imprecise or inarticulate *description.* *Apparent confusion over the use of gravitational force and gravity.*
Int:	And how do you know when gravity is present?	*s-/d-* No *causal explanation.*
Stu:	Everything must come to the Earth's surface, no matter at what height, everything must drop ... in comparison to say if it was in space, then things would be floating because there is no gravitational ... there is no gravity in space.	-5G1 No gravity in space -(Stead & Osborne, 1980), (Watts, 1982)
Stu:	Basically everything has this "mg"... weight, on Earth.	*-s/-d weight concept poorly articulated and earth-bound.*
Int:	And how would you know if it wasn't present?	
Stu:	Well if it wasn't present we would be all floating I guess, we wouldn't be walking on the Earth's surface, things wouldn't be stationary on the Earth's surface, Yeah.	(Nelson, 1991) (-N1) Floating & *motion related to gravitational force - possible confusion over inertia vs weight.*

49. frameworks 1 and 2.

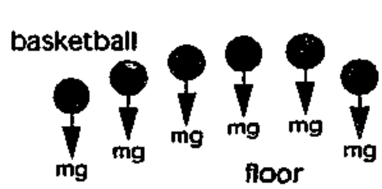
50. framework 7.

51. framework 5.

7.2.8.2 (b) Projectile probe

Int: Does that diagram look correct to you?. Stu: Well in the first 4 shots … gravity is acting all the way through. No doubt about it., Int: Why? Stu: Because of the speed of release is overcoming gravity.	variable/selective action of gravity (cf. Watts, 1982, p.120) - (framework 7).
Int: So it's going pretty fast, and then it drops a little bit? Stu: Yeah. it's a very slight degree, but it really takes over here <*near the end*> as the ball is slowing down as gravity plays a much greater effect. Int: Why do you think it comes in there <*apex*>	+G5 (FCIM) -> +I3? (FCIM) Possible impetus view. Selective effect of gravity related to speed - more speed less effect of gravity (cf. McCloskey & Kohl, 1982)
Stu: It's some special point. Like it's gone up. And then it's coming down faster. Int: Do you think there is something special in that?	gravity 'takes over' (Watts, 1982) (framework 5).
Stu: I guess its, ah, running out. Speed's decreasing due to the distance it's overcome. I mean, of slowing down to a halt and then this "mg" thing sort of … I mean gravity is always pushing it down, but it will have more effect in pushing it down because I guess the ball's sort of come to the end of its …	possible dissipation of impetus; +I3? (FCIM). +G5 (FCIM)
Stu: It loses KE and PE I guess, and … potential energy. Int: What was your explanation? Stu: Well it has a certain amount of PE and then as it goes up, PE turns into KE … and PE is … Int: What you are telling me is that at the apex it has run out of KE and then falls again? Stu: Or is it the other way around? … <long pause> I can't work that one out.	Confusion over conservation of energy and 'PE' versus potential energy! Erroneous argument on energy conversion PE-> KE on ascent. Ignores horizontal component of motion

Figure 7-27: Steve's projectile probe diagram.



7.2.8.2 (c) Summary

Steve appears to have no cohesive, overall model of gravity, but rather, appears to have piecemeal explanations for various aspects of it, i.e, in Lawler's (1985) terms, different methods for each data element about gravity. This is consistent with his weakness with N1-N3 and gravity (as predicted by the FCI), whereby poor

Newtonian understandings make it difficult to relate the events in these probes to a coherent conceptual schema.

7.2.8.3 Video Probes

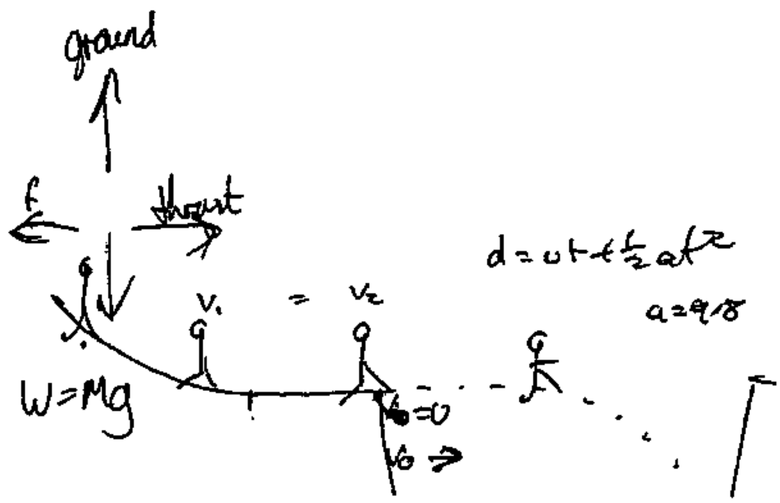
Steve demonstrates a superficial understanding of these contexts, demonstrating poor understandings of the nature and magnitude of gravitational forces and fields, and an apparent 'support or fall' model of gravity (cf. Bliss, 1989).

7.2.8.3 (a) Homer's leap

Steve explains the expected parabolic trajectory in terms of the projectile motion equation (Figure 7-28) +5G3 (FCI) — in contradiction to his possible weakness about this indicated by the FCI (Table 7-25), but later confuses the vertical displacement with the length of the path (1:305). Similarly, he correctly applies N3 to discriminate between weight and the reaction force from the ground (again in contradiction to the FCI), but then incorrectly applies it to explain the thrust that is responsible for Homer's forward motion (1:236):

Stu:	… um Newton's laws …third law I think – there is an equal and opposite force for each and every reaction, so there is friction there, there is thrust there going forward and mg going down… and then the equal option is the weight ah the force of the ground pushing up.	(refers to Figure 7-28) +N3 correctly identifies vertical reaction pair. -5S3? (FCI) -N3 confuses friction with a horizontal force on the slope. No mention of normal reaction.
Int:	Where does the thrust come from? … <long pause>	s-/d- inconsistent response
Stu:	The thrust is … coming from, from … I guess the increase in the speed of the wheels.	-N3? -N2.2 (FCI). Active force notion - AF2 (motion -> force)?
Int:	So it was the slope that was causing the acceleration?	
Stu:	Yeah.	
Int:	So that would what have the same velocity horizontally at those two points? (v_1 and v_2 in Figure 7-28).	s-/d- consistent with above - no slope, nor thrust but does friction cease here too?
Stu:	Yeah. I would agree with that.	

Figure 7-28: Steve: explanation of Homer's leap.



7.2.8.3 (b) Road runner probes

The notion of support[52] (e.g., Bliss, 1989; Galili, 1996, p.231) appears to underpin Steve's understandings of the inertial events depicted in these probes. He has a functional model of gravity, in which gravity 'brings everything down to the Earth's surface' (1:73), and in which gravitational acceleration is mass-dependent (1:179) (-N2; +5G3 FCIM). He also, however, inconsistently argues that 'gravity' is 'universal' (1:194). He regards the elasticity effects as being incompatible with a rigid vertebrate skeleton (1:101). These are consistent with his responses to the 'gravity' probes above[53], and his poor understandings of the NFC (Table 7-24) and gravity (Table 7-25).

Steve demonstrates a support or fall model in a number of situations, for example:

Stu: There is no surface there after the cliff so it[54] is causing him to fall (1:80)

52. see Figure 4-14 on page 123.

53. see Section 7.2.8.2 (a).

54. i.e, gravity.

and later 'support' seems to be intertwined with a resistance in a model in which the balloon's buoyancy is explained as being due to air resistance, which presumably provides support by stopping the balloon falling rapidly:

Stu: Well, Ok, if the balloon blows up, then he has got no more … I mean the balloon is obviously catching air[55], it's slowing him, it's resisting … that mg effect[56]. Um … his weight effect. It's slowing down, I mean due to air resistance, there is a resistance I guess.
Int: The balloon?
Stu: Yeah. And obviously when it bursts, that doesn't exist any more and there is no more of that catching effect of the wind[57], I guess he is just free falling … free falling under his own body weight. (I:148)

He appears to have little quantitative understanding of gravitational force and N4 when he argues that the gravitational field of the balloon might have attracted a dart to the balloon (I:137).

7.2.8.4 Planetary computer probes

Steve's responses to these probes are predicated on a field-based model that shows confusion about the nature of gravitational fields (I:552) and what they represent.

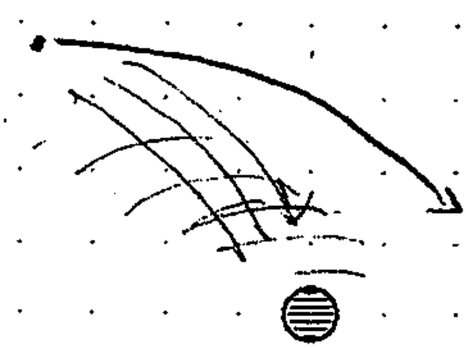
7.2.8.4 (a) Single-planet probes

Steve identifies both a 'point-to-point' gravitational attraction between the planet and the asteroid, and a gravitational field around the *planet*, which he represents as 'field lines' (Figure 7-29), but *not* around the asteroid (I:425). This is possibly because, as below, he is uncertain about whether the asteroid has any gravitational significance (-N4, -5G1 FCI), suggesting a geocentric (but inconsistently applied)

55. n.b. the probe depicts a 'normal' hot air balloon with a narrow orifice, not something akin to a parachute.
56. presumably refers to buoyancy.
57. no obvious wind is depicted in the probe.

notion that gravity is intrinsic to mass (in this case the planet), as opposed to a force between masses (N4) (cf. Arons, 1990, p.70; Galili, 1993). The asteroid presumably is either too small to 'create' gravity, or perhaps only planets have gravity.

Figure 7-29: Steve: gravitational field structure around a planet[a].



a. The arrows show the direction the asteroid would move under the influence of gravitational force. (I:558).

The reasons for this are unclear, suggesting considerable uncertainty about gravity. (-5G3 FCI), and N4 (-N4):

Int: And those lines are what? Representing...?
Stu: Gravitational field I guess.
Int: Is this the gravity of the planet, or is it of the whole system?
Stu: <long pause> That is gravity of the whole system.
Int: ... So does the asteroid cause any gravity?
Stu: If I said yes then I wouldn't be able to explain it!
Int: But you think it does?
Stu: Yes.

Subsequent probes elicit further confusion about gravity, and his inability to use N4 to support his arguments (I:513):

Int: It has bent around a lot more hasn't it[58]?
Stu: Yeah. Definitely.
Int: Why do you think it bent around so severely?
Stu: Well the distance part was much smaller so ... I guess this gravitational effect plays much more ... has a much more bigger role.

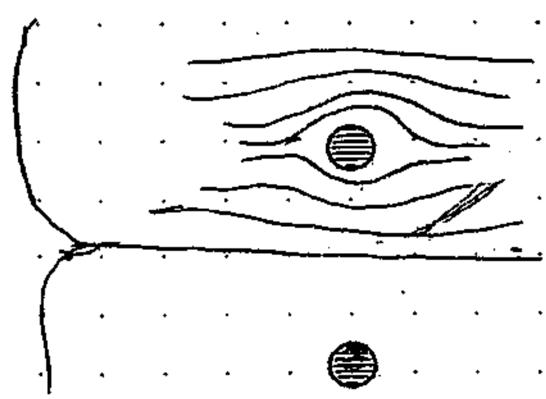
58. This refers to the asteroid's path after increasing the mass of the planet.

Int: So the gravity has changed what?
Stu: The distance!
Stu: Over there it really does go fast, ... so what has the gravity actually changed for the asteroid?
Stu: The field strength!

7.2.8.4 (b) Dual-planet probes

In describing a field structure around the planets (Figure 7-30), Steve demonstrates misunderstandings of superposition (-4S4.1), and cancelling of forces[59] (-4S4.2), as well as of the nature of gravitational fields (1:552):

Figure 7-30: Steve: gravitational field structure around a binary planetary system.



Int: So these are field lines?
Stu: Yeah, ... It gets to a point where they shoot out and cancel each other out. And if they are equidistant I guess that's why ..., they are not going to be sort of repelled, um attracted, in to their field sort of lines.
Int: If it gets attracted into one of those field lines, will it move along one of those lines?
Stu: Yeah. It gets attracted to ... either one of the planets.
Int: So what is the relationship between those lines and gravity.?
Stu: I don't' know ...Um ...gravitational field lines.
Int: So if a particle gets attracted into one of those field lines, does it move along the line?
Stu: Yeah! Oh it would bead in sort of thing.

s-/d- Incorrect field structure drawn and cancelling at ends wrong: -N4, -S4.1, -S4.2 (FCI). No cancelling on interplanetary line. -S4.1, -S4.2

s-/d- -N4 (cf. Figure 7-29) confusion over

s+/d- -SG1, -N4 No relationship given.

s+/d- Confusion over the meaning of the representation? Subsequently (1:589) talks about the asteroid 'running along the field line'.

59. i.e., at the midpoint of the line joining the two planets.

Int: What about the ends?	
Stu: The gravitational field doesn't allow it to continue on.	-N2?, -N4, -S4.1
...	
Int: How do the branching lines explain why it stops at the ends?	-N4, -S4.1, -S4.2 *Confusion evident.*
Stu: Ah ... I can't answer that.	

7.2.8.4 (c) Multi-asteroid probes

These probes caused Steve to question his field model when he became confused[60] as to why some asteroids were attracted radially towards the planet, rather than following curved paths (i.e., across the field lines as in Figure 7-29).

Int: Can you try and explain this one? (l:690)	*(refers to probe G8)*
Stu: They are always getting attracted back to the Earth – gravitational attraction.	s+/d- *equal and opposite force of attraction.*
Int: How does that relate to your field lines ... around the planet? ...	*Confuses direction of motion with the structure of the field.* Force is perpendicular to the field lines[a].
Stu: I had it the other way round didn't I!	
Int: So what do you think is happening here?	
Stu: I guess the field line changes, I guess, with the direction of the gravity of the asteroids.	s-/d- *Unable to explain superposition* -S4.1 FCI
Int: So it changes the field strength?	
Stu: Yeah. It does.	

a. i.e. 'lines' of equal gravitational field strength.

7.2.8.5 Vector probes

No further issues were raised by these probes, which Steve felt confirmed his understandings, with force and acceleration vectors representing the gravitational attraction, and (as above) remaining confused about the relation between force and field in arguing that the tangential velocity vectors demonstrating 'curving across the field lines'.

60. with probe G8.

7.2.9 Alan

Alan is undertaking major studies in both Chemistry and Mathematics, and a sub-major in Physics. Alan's self-assessment of his knowledge of both Physics (in general), and the area of Mechanics in particular, were both 'good'. His physics background is considered to be normal, with three years of studies in Physics completed (Table A-10 on page 6).

7.2.9.1 FCI questions

The FCI data (Table 7-27) indicate that Alan has a poor understanding of the NFC. His understanding of gravity (Table 7-28) (as measured by the FCI) shows probable difficulties in all three categories. Potentially severe difficulties with N2, N3 (Table 7-27) may make it very difficult to explain most of the events depicted in the probes. Consistent with his poor N2 and N3 understandings, his FCI-predicted misconceptions (Table 7-29) indicate potential misconceptions related to impetus, active force, and action-reaction pairs, and concatenation of influences, all of which may make it difficult for him to articulate correct or coherent Newtonian answers to the probes.

Table 7-27: Alan - FCI results by category.

FCI category	0 Kinematics	1 NI	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	2	4	0	0	2	6	33%
Percentage	33%	50%	0%	0%	50%	38%	

Table 7-28: Alan - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	3	0	1
Percentage	50%	0%	50%

Table 7-29: Alan - predicted misconception areas[a] (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	K1	K2	K3				
	×	×	✓				
1. Impetus	I1	I2	I3	I4	I5		
	✓	×	✓	✓	×		
2. Active Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7
	✓•	×	×	×	×	×	✓•
3. Action/Reaction pairs	AR1	AR2					
	✓	✓					
4. Concatenation of influences	CI1	CI2	CI3				
	×	×	✓				
5. Other influences on motion	CF	OB					
	×	×					
5.1 Resistance	R1	R2	R3				
	×	×	×				
5.2 Gravity	G1	G2	G3	G4	G5		
	×	×	✓•	×	✓•		

a. A '•' in a cell means that only one of a number of same-category misconception indicators was chosen.

7.2.9.2 Introductory questions

Alan's weak understandings of the NFC and gravity (cf. Table 7-28) are reflected here, where he (inconsistently) demonstrates a possible belief in active agency (+AF1, +AF7 FCIM) and the selective action of gravity (cf. Stead & Osborne, 1980; Watts, 1982). Gravity is correctly described as a force between two masses, N4 is described in general terms (i.e., varies with mass and distance in an undefined manner (-N4)). He has a 'field-like' model of gravity, but with zones of uniform, as opposed to continuously varying, field strength (-5G1 FCI), with the field indicating the magnitude and direction of a resultant force that would act on a mass[61] placed in the field. Why he holds this zone model is unclear from the data, but may be a non-mathematical way of describing a continuously variable field in the absence of expounding a causal model such as N4 — i.e., a non-mathematical representational form of a gradient (cf. representation as an element of T-PCK: see "Representation" on page 62).

7.2.9.2 (a) Gravity

Int: Can you tell me what you understand by Gravity?	
Stu: It's an attraction between two masses, ah, which increases with the size of each mass and decreases with the distance between the two masses.	s+/d- relationship not fully articulated (mathematically). +N4
Int: And how do you know when it's present?	
Stu: To measure it on an object ... I guess you could observe its motion. If it's a free body it will act towards another object ... but on a small scale.	s-/d- poss. assumes low mass (cf. planetary mass)? -> weak force. -N2 Not fully articulated.
Int: How do you feel it in your own body?	
Stu: Normally when you are standing on the ground, you feel sort of the weight of your body acting through the rest of your body ... pushing down through your feet... so you feel that weight being pulled down. But when you are falling, you don't feel that weight through your body and your whole body is moving towards the Earth, which is where the gravity is acting, and there is nothing stopping that motion. It's that stopping of gravity that you normally feel.	Confuses weight with reaction force. mass with weight ('weight being pulled down'). (cf. Arons, 1990, p.70; Galili, 1993, 1995; Trumper & Gorsky, 1996) Gravity acting on (or at) the Earth (or at the surface?) or on the person? (cf. Nelson, 1991) Stopping vs. opposing - does gravity cease to act?
Int: By the stopping of gravity, you mean the feeling on your feet when you are standing on the ground?	-N3 v. poorly articulated.
Stu: Yeah. The opposing of gravity is what you feel.	
Int: And where do you find gravity?	
Stu: Absolutely everywhere.	s+/d-
Int: What do you think of when, you think about gravity?	
Stu: I kind of picture it as zones of strength ...	Notion of 'flow' of zones of strength (as opposed to gravity) implies 'regions' of identical value as opposed to a continuous gradient. (No conceptual basis for a zone model - perhaps PCK?)
Int: What do you mean by these 'zones'?	
Stu: Sort of like a flowing zone. Like it's increasing in here and weaker in that area. A continuous type flow of strengths through weak and strong and then back to weak again... whatever.	

61. cf. unit mass.

Int:	If you had to draw one, what would you draw?	
Stu:	Ah… I would draw a field. And if you put an object in that field, you could sort of get a resultant force that would act on that object … ah vector force going one direction at a certain strength.	s+/d+ Correctly describes force vector at a point in a field.

7.2.9.2 (b) Projectile probe

Int:	… What's happening there with gravity?	
Stu:	Well through that bit there, its' actually a straight line, which is wrong,…it should still continue to curve and it's going to do that.	+5G3? detects incorrect (linear) path at the start.
Int:	So you think this diagram is a bit wrong?	
Stu:	… It suddenly hits a point where it goes… "nuh, I'm slowing down" or something, and decides it's going to start acting under gravity. Looks Ok through there …	-N2.2 (FCI) s+/d- Active agency of ball (semantic or conceptual?) and selective action of gravity (cf. Watts, 1982,p.120)
Int:	That end?	
Stu:	Yeah. The other end is wrong	
Int:	Ok. Now where is gravity acting on that diagram?	
Stu:	Should just be acting straight down at each … same strength, same direction.	Contradiction to above.

7.2.9.2 (c) Summary

Alan determines that gravity is a force between two masses (+5G1) that varies with their mass and distance in an unspecified manner (-N4), and is aware that it can be represented as a vector field representing the force on a mass at a point in the field. His field-model, however, is incorrect. He appears to hold misconceptions about active force (+AF1, +AF7 FCIM), and the selective action of gravity (e.g, Watts, 1982)[62], and, consistent with his FCI results, has difficulty in applying N2 and N3 (-N2, -N3), apparently having considerable difficulty in contextualising his knowledge. He occasionally provides defining (d+) responses to questions.

62. framework 7.

7.2.9.3 Video Probes

Projectile motion is caused by gravity acting constantly downwards, and should follow a parabolic trajectory (+5G3 FCI). Gravity, however, acts selectively on objects (-N2, -5G1 FCI) e.g, accelerated motion (as opposed to a constant acceleration with a constant force). The inertial and elastic scenarios are unrealistic cartoon artefacts.

7.2.9.3 (a) Homer's leap

The selective action of gravity (cf. Section 7.2.9.2 (b) above) explains Homer's acceleration down the hill, and the Ollie is explained (correctly) in terms of conservation of momentum. However, while having difficulty in articulating clear Newtonian arguments, Alan subsequently produces a reasonable 'Newtonian' graphic representation (Figure 7-31), with gravity acting vertically downwards, a component of which causes acceleration down the hill, and a normal reaction force from the hill. The expected trajectory is parabolic. In Figure 7-31, gravity appears to be constant, and there is no indication of how gravity acts selectively, as is implied above — which Alan subsequently contradicts — '... well g's would be the same' (1:357). This essentially Newtonian representation is in stark contradiction to his poor FCI scores for both the NFC (Table 7-27), and for gravity (Table 7-28) — an issue examined below in Section 7.4 on page 347.

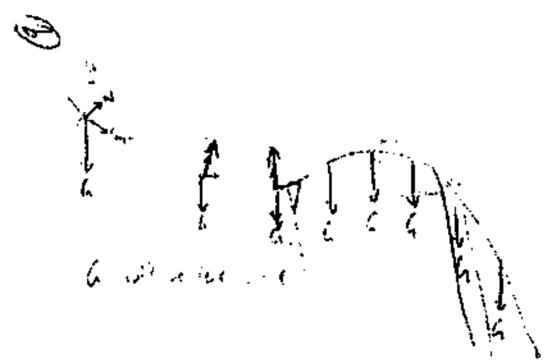
Stu: (1:291) Gravity sort of acted slowly at the start when he was ... as he started to fall, and then he sped up on the way down ... on the way down the hill and ... he had all the momentum which had been converted to horizontal velocity ... like yeah the force vertically had started him moving down vertically and the ramp had changed his direction ... applying a force to him...	+G4 FCIM? (*cf.* Watts, 1982)[a] s-/d- confusion/misconception here about 'conversion' of momentum (mv) to velocity (v). s-/d-

a. frameworks 5 & 7

However, Alan does not fully understand the significance of what he has represented in the diagram (-N2, -5G1 FCI), verbally contradicting what he has displayed in Figure 7-31:

> (1:357) … ah force has him accelerating in that direction, and that just sort of gradually changes until his, until the force gets very small, and then there is no horizontal force any more once he's travelling horizontally…*there's no forces at all once he's travelling horizontally.* (emphasis added)

Figure 7-31: Alan: Diagram explaining Homer's leap.



Conservation of momentum explains why the Ollie is not correct. It is not clear if Alan recognises that the force[63] would be impulsive (rather than constant), and what effect that would have on the relative motion between Homer and the skateboard, if any (cf. James' response on page 302):

> Because … conservation of momentum… thinking about him and the skate board… an internal force between the two of them … him kicking off …acts between him and the skate board and that momentum will continue because there is no other, there is nothing else acting within that system. (1:336)

7.2.9.3 (b) Road runner probes

Alan dismisses the elastic deformation scenarios as an 'annoying' cartoon artefact. In projectile motion, falling is due to the absence of a counteracting normal reaction

63. i.e., as Homer jumps upwards (on the assumption that this can, in fact, be done).

force — as with the Homer video, allowing gravity to act; making objects fall at the same *speed* because of air resistance (1:268) (-N2.2 FCI, +AF6 FCIM).

7.2.9.4 Planetary computer probes

Radial gravitational fields (+5G1) and superposition of forces (+S4.1 FCI) underpin Alan's responses, which demonstrate good understanding of the events, with a reliance on descriptive, as opposed to mathematical and formal Newtonian[64] responses.

7.2.9.4 (a) Single-planet probes

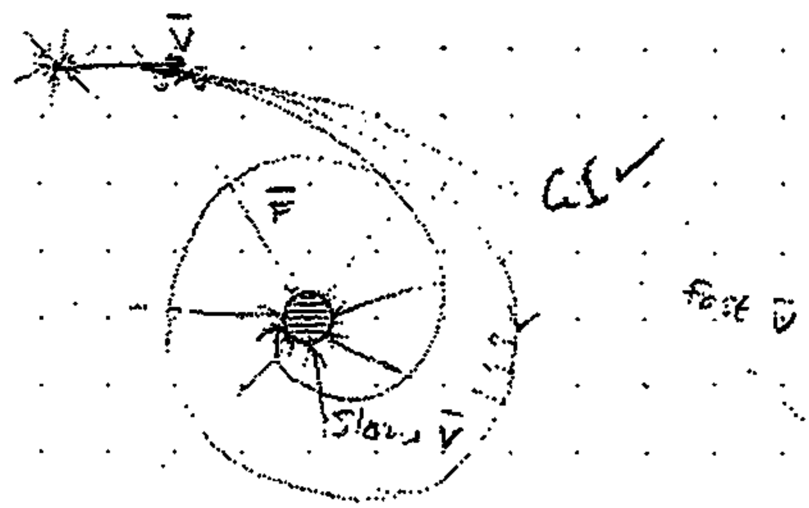
Alan describes a radial gravitational field around each mass, representing them as radial lines of force (cf. Figure 7-30) whose magnitude decreases with mass, and with increasing distance in an unspecified manner (-N4). Gravity causes the asteroid to accelerate towards the planet[65], the effect of which depends on its velocity (as in Figure 7-32).

Stu:	(1:424) If you were to draw the gravitational field around the planet, it would be acting in towards the planet… all the way around it. … straight towards the planet assuming there is absolutely nothing else around it for a long time. … and the strength of the field decreases further out along these field lines you go. ….	*s+/d-* -N4 relationship not specified. Awareness of perturbation to field caused by other mass objects (cf. Figure 7-34)
Int:	So what does the force change on the asteroid?	*s+/d-* -N2 force -> <u>acceleration</u>: poorly expressed – cf. magnitude and/or direction.
Stu:	Ah it changes the direction of its velocity, and probably its speed a little bit too.	
Int:	What can you say about gravity for the asteroid?	
Stu:	Yep. Its also going to have the same type of thing around it … the forces are going to be smaller because its a smaller mass, and they are also just going to get weaker the further out you go along those lines.	+5G1 FCI

64. i.e., explicit use of, or referral to, N1, N2, N3 or N4.

65. poorly expressed in terms of vector attributes.

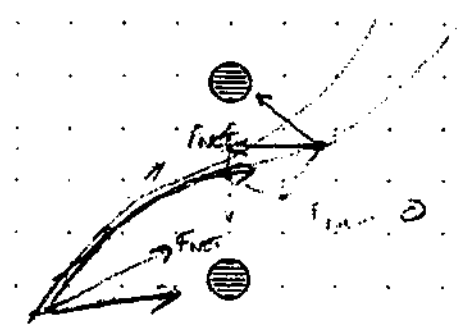
Figure 7-32: Alan: radial forces on a passing asteroid moving at different speeds.



7.2.9.4 (b) Dual-planet probes

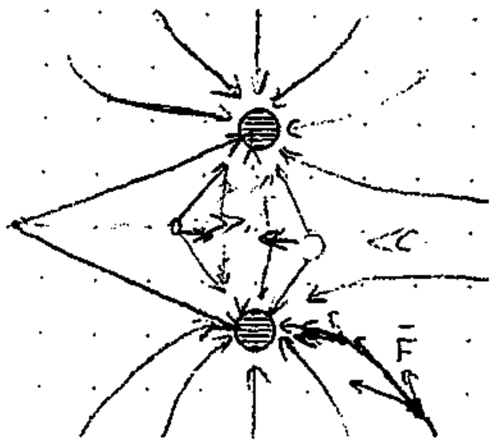
Alan uses a parallelogram of forces representation (+S4.1) in conjunction with N4 to account for asteroid motion (+N4) (Figure 7-33).

Figure 7-33: Alan: Forces acting on the asteroid.



The oscillatory motion in probe G4 is a result of the unique geometry in which the 'vertical' components of the gravitational force towards each planet cancel each other (+S4.1) (1:654). However, in explaining the magnitude of the horizontal nett force, he draws force vectors to each planet (Figure 7-34), (starting farthest to the left) and as he 'fills in' ones closer to the planet, erroneously and inconsistently argues that the gravitational force increases with distance from the planet (-N4), (i.e., as the vectors, *as drawn*, increase in length *away* from the planet) presumably being confused by the graphic representation (1:666). However, his representation of the field around the planets (as *lines of force*[66]) is essentially correct.

Figure 7-34: Alan: field structure around the two planets.



7.2.9.4 (c) Multi-asteroid probes

These probes supported Alan's radial field structure, with asteroid motion in the probes being due to their different distances from the planets resulting in different forces acting towards, and subsequently around, the planets. There was no recognition of intra-asteroid interactions.

7.2.10 Anne

Anne is undertaking a double-major study in English, and a sub-major study in Physics. Anne's self-assessment of her knowledge of both Physics (in general), and the area of Mechanics in particular, were both 'good'. Anne's physics background is considered to be normal, with three years of studies in Physics completed, and additional studies in first-year Chemistry and Earth Science (Table A-11 on page 6).

66. as opposed to equipotential surfaces.

7.2.10.1 FCI questions

The FCI data (Table 7-30) indicate that Anne has a moderate understanding of the NFC. Her understanding of gravity (Table 7-31) (as measured by the FCI) shows good understanding of all three categories. Her apparent difficulties with N2 might affect her ability to explain many of the events depicted in the probes. Her FCI-predicted misconceptions data (Table 7-32) shows many single selections of incorrect responses from a larger set of same-category items that may indicate some confusion about particular aspects of the NFC[67] including active force (AF1, AF4), action-reaction pairs (AR1), impetus (I4), and gravity (G1, G2) — areas of significance in all of the probes. There is a likely misconception about concatenation of influences (CI3).

Table 7-30: Anne - FCI results by category.

FCI category	0 Kinematics	1 N1	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	4	5	1	3	2	11	62%
Percentage	67%	63%	25%	75%	50%	69%	

Table 7-31: Anne - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	4	2	2
Percentage	67%	100%	100%

67. n.b. Hestenes' cautions as described previously.

Table 7-32: Anne - predicted misconception areas[a] (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	K1	K2	K3				
	×	×	×				
1. Impetus	I1	I2	I3	I4	I5		
	×	×	×	✓•	×		
2. Active Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7
	✓•	×	×	✓•	×	×	×
3. Action/Reaction pairs	AR1	AR2					
	✓•	×					
4. Concatenation of influences	CI1	CI2	CI3				
	×	×	✓				
5. Other influences on motion	CF	OB					
	×	✓•					
5.1 Resistance	R1	R2	R3				
	×	×	×				
5.2 Gravity	G1	G2	G3	G4	G5		
	✓•	✓•	×	×	×		

a. A '•' in a cell means that only one of a number of same-category misconception indicators was chosen.

7.2.10.2 Introductory questions

Despite having a good FCI score on the gravity components (Table 7-31), Anne's responses lack causal descriptions or Newtonian explanations, and demonstrate apparent confusion about the nature of gravity and its action (-5G1, -N4). She frequently responds in ways that are categorised as s-/d-, indicating a potential lack of content knowledge, or perhaps a weakness in contextualising knowledge to new situations.

7.2.10.2 (a) Gravity

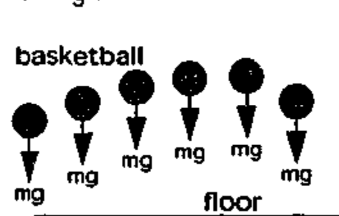
Int: What do you think of when you hear the word 'gravity'? Stu: Things falling. Int: Do you think of it as a force, or field, or is it just the motion of the objects that you think about when you think of gravity?	s-/d- -N4 No causal model, nor mention of scientific or mathematical relationships. (N⊖)

Stu: Ah, probably in the general context, you think of things falling, but I suppose as a physicist, you think of things being pulled as … there is a force acting on an object. **Int:** What is your best example of gravity and why?	-5G1 (FCI) falling versus acceleration - *no mention of force between masses.*
Stu: Um… <long pause> probably dropping something up high. You could talk about gravity, and acceleration, and how it is pulled towards the centre of the Earth I guess. **Int:** Where do you find gravity?	s-/d- Links gravity and acceleration *here* (cf. *above*) and terrestrial gravity. (+5G1?)
Stu: Um… well for a teaching context, you would talk about it within the context of planets or the Earth mainly, but it's around planets, things that interact together. **Int:** So how do you know when it's present?	s-/d- Interacting masses but no formal explanation of meaning wrt. gravity. Gravity '*between*' interacting objects or '*around* planets(?) Selective action or location?
Stu: Well, it's probably for us, to take it out of our own context, to know when it's not present. Um, so, um, on the Moon it's a lower gravitational acceleration. So, um… We don't usually realise that it's present because we are used to it. So … in terms of explaining it to kids, on how it's not…, how it's present, that they, …but it's within their own experience, so they can't sort of understand that it's…. They are used to it being there.	-N4 - *confusion evident* - implicit argument that it *can not* exist in some places - *poss.* confusion with low gravity as *opposed to* <u>none</u>.

7.2.10.2 (b) Projectile probe

Int: Was the motion a realistic motion? **Stu:** Um… um, I think… yeah I guess it would be. Just trying to think how… I guess it would be… **Int:** So you don't find any problems with it? **Stu:** No! **Int:** Is gravity acting in this environment?	-5G3 (FCI) fails to *detect* incorrect path.
Stu: Well gravity is acting because um the ball is falling after this point here, also it's slowing down, I mean it's not travelling as far, um … the acceleration, it's being decelerated through this part because it's not travelling up as high. It's a bit hard to see, but that's probably a better example, where it's travelling further, height wise, in the time.	s-/d- identifies *effect of acceleration* on trajectory in the first half of the motion (to apogee).

Figure 7-35: Anne's projectile probe diagram.



7.2.10.2 (c) Summary

Gravity is a radially directed, geocentric force that acts on objects (as opposed to between masses) to make them fall[68] (cf. accelerate - which is used inconsistently) to the Earth. Gravity also exists on and around planets and 'things that interact together but, apparently, may cease to exist in some circumstances (-5G5, -N4).

7.2.10.3 Video Probes

Anne's apparent inability to describe events in Newtonian terms is contradictory to her FCI score, and suggests that she may either have difficulty in contextualising physics concepts to 'real world' contexts, or that she has shallow understandings of the NFC and gravity that she is unable to articulate in a face-to-face situation (as opposed to her demonstrated ability to do so in examinations in the B.Ed.(Secondary), where mathematical representations predominate).

7.2.10.3 (a) Homer's leap

Anne has difficulty in expressing the events depicted in the probe in appropriate and consistent Newtonian terms, demonstrating particular problems with explaining N3[69] (i.e., normal reaction), resolution of vectors, and projectile motion:

> ...he would have his weight force going down, but because he is on an angle, he's got a component of it pushing him down the slope. And at the bottom he has got quite a lot of motion.... so he's got quite a lot of kinetic energy and he has still got his weight force down there actually, um yeah, so he's obviously accelerated down there, and then he sort of flies off. Now here he still has his weight force going down... (I:178)

68. Falling is indicative of gravity.

69. in apparent contradiction to her FCI score on this category.

Anne believes that the subsequent events are wrong, identifying an incorrect trajectory and sudden fall (+5G3 FCI) (suggesting that it is simply a cartoon artefact (l:170)), but provides only brief, partially complete, reasons (s-/d) with little coherent Newtonian argument as for why this is so. She dismisses the Ollie scenario as unrealistic, and has the basis of a correct answer, but is unable to explain it in appropriate Newtonian terms.

Int: Remember that he does a little dance on the skate board? (l:188) Stu: Yeah, that doesn't make sense. Int: Why doesn't it make sense? Stu: Because for him to do that he would need to be pushing down on the skateboard for him to be able to jump up. Int: Right ... Stu: Um, and the fact that the skateboard just stays there and he does that little skip and lands back down on it, um, wouldn't um, yeah that wouldn't be able to happen in real life.	*s+/d- recognises need for a reaction force to produce acceleration (+N2.1, N3.1? FCI) but no discussion of feasibility/cause in free fall context (cf. James, Section 7.2.7.3 (a) on page 300)* *s-/d- no causal argument (NΘ), nor mention of impulsive force or even if it is possible.*

7.2.10.3 (b) Road runner probes

Elastic body deformation and projectile motion depictions (curve and sudden drop) in Probe 1 are both considered incorrect, because gravity would (a) act equally over the body (l:64), and (b) cause the objects to fall (l:78) (cf. response in Section 7.2.10.3 (a)).

Stu: (l:78) Well when something is projected into the air and we see what happens to it, so gravity would pull it down, so obviously he was out of a gravity field because he just went straight ahead.
Int: So you think that's correct or incorrect that he did that?
Stu: Incorrect, ...that's incorrect.

Both the rotation during falling and the elastic rebound scenarios in Probe 2 are also considered incorrect (l:87), but no Newtonian reason is given (NΘ). The inertial events depicted in probes 3 and 4 are incorrect because gravity '...would have acted equally on everything' (I:109). The depiction of objects falling at different speeds is likewise incorrect, but small variations may be possible because of different forces (due to air resistance) acting on each falling object (I:143).

7.2.10.4 Planetary computer probes.

Anne determines that interplanetary gravity is a uni-directional, point-to-point force (-N4, -5G1), and that gravity *around* a planet can be represented as a field. She is apparently confused about the relationship between force and field, and their representation, and has difficulty in interpreting vector representations of force, leading to inconsistent arguments. For reasons that are unclear, orbiting bodies are presumed to follow a circular path.

7.2.10.4 (a) Single-planet probes

Anne describes a uni-directional, point-to-point, gravity force towards the largest planet (-5G1), with the asteroid also experiencing some force, but not necessarily of the same magnitude (-N4):

> Well gravity, um, would be acting between these 2, so there would be some kind of force between them, and it would be acting towards the larger body. Now the asteroid would be experiencing some force um… because of this larger planet. (I:296)

She apparently understands N4, but does not seem to be able to apply it precisely to these probes[70]:

> Well the gravitational acceleration depends on the masses, and I think it's proportional to $1/R^2$ I think, but we did the distance, so it's the distance away, $1/d^2$, whatever it is… (I:309)

70. i.e., is 'distance' the centre-to-centre distance, or the surface-to-surface distance?

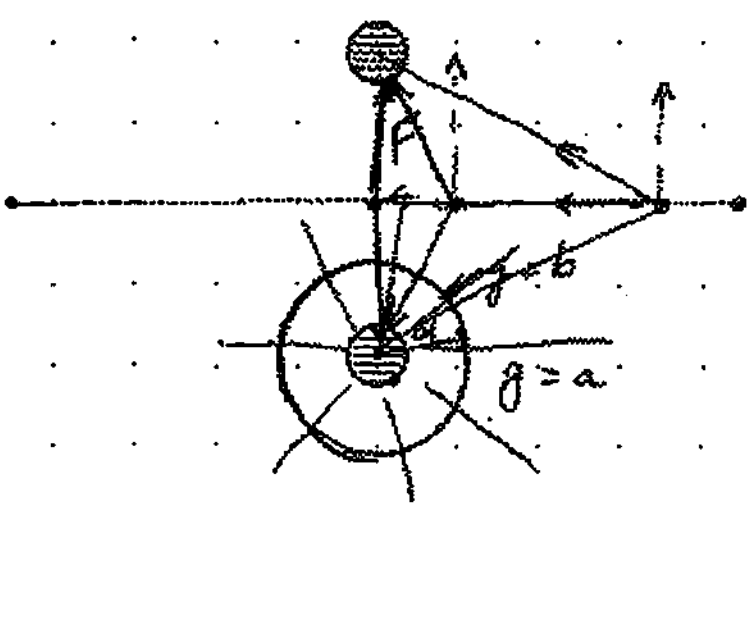
She apparently has little knowledge of Kepler's laws, or perhaps what they mean in this context, or how they, or N4, might be used to explain or describe orbital motion — which she expects to be circular (1:316):

Stu: It's a very strange orbit but it's actually orbiting! (1:344)
Int: Well it's extremely elliptical. What makes it do that?
Stu: Um, well … um… … cause its speed is changing so it goes very slowly around this end, and it speeds up around this end, and speeds up when it goes around.
Int: Why?
Stu: Well the force of gravity on it is least out here, cause it's furthest away… is that right. Yeah I think it is. So um,… what did you ask me, …how does it happen?
Int: Why does it orbit?
Stu: I can't think. I don't know!

7.2.10.4 (b) Dual-planet probes

In Figure 7-36. Anne depicts the superposition of gravitational forces (+S4.1 FCI) from the planets, and the reason for the oscillation. However, she is confused about the relationship between gravitational force and the representation of a gravitational field. This is demonstrated by her confusion about the what the circle around the lower planet in Figure 7-36 actually represents:

Figure 7-36: Anne: gravity and force in the oscillation scenario.



Stu:	(l:382)… If it's the same distance from the centre of that, then it will be constant. So it's sort of got like lines, you know … where it varies.	s-/d- -N4 relationship not given. Describes a representation of equipotential surfaces.
Int:	Lines of what?	
Stu:	Well it would be gravitational field.	
Int:	So the gravitational field around here are circles around the planets are they? … On the diagram?	Uncertainty about what is being represented.
Stu:	No.	
Int:	But you talked about circles around the planet.	
Stu:	Yeah, but it's not. Gravitational field is not circles, it's straight lines. …	s-/d- Confusion over direction of force and representation of gravitational equipotential surfaces in both of these responses.
Stu:	(l:406) Um, I think gravitational field is straight lines going to the centre of the circle. I think. I don't know! … but that's gravitational field strength? I suppose it is!	

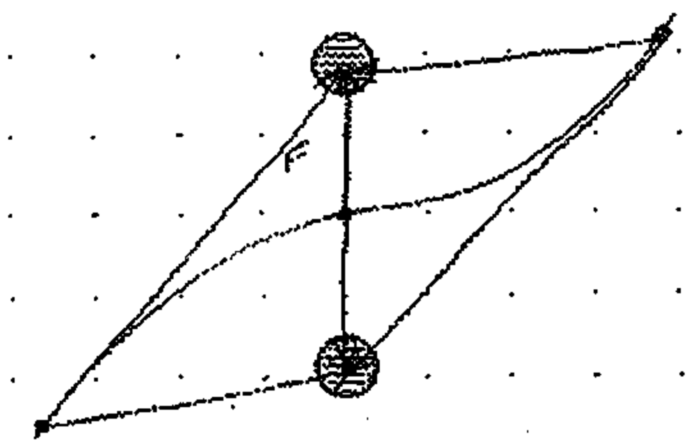
The oscillatory motion of the asteroid is explained in terms of the components of the gravitational forces from the two planets, which, in apparent contradiction to her understanding of N4 (l:309), *increase* with distance (-N4) (l:424):

> I think this is right, because the components of that force are pulling back to the centre, um as it moves further away from the centre point, the components of the force being… pull it back, So um … so the… if you like … The horizontal component gets larger the further away it gets. And that's why it slows down.

However, in the subsequent probe (Figure 7-37) she argues the opposite (l:454):

> But what I forgot about over here is that it's getting less as it's getting further away. Because the components are changing as it's getting further away… but because it's further away… the force of gravity is less.

Figure 7-37: Anne: forces acting on the asteroid.



Subsequently[71] she implies that the largest force causes the slowest motion, which may be a consequence of her poor understanding of N2[72] (I:496):

Int: Is this consistent with your explanation of the previous one? (Figure 7-36)
Stu: I think I would say I am unsure… probably.
Int: Because?
Stu: Because it's slowing down and speeding up. And also because the slowest points are furthest away…from the opposite planet … thing.

7.2.10.4 (c) Multi-asteroid probes

An increase in gravitational force with *increasing* separation is used to describe the motion in probe G7 (I:530), however, with probes G8 and G9, Anne argues the opposite, for example (I:618):

> Because this one is the closest, it's under the greatest force from the planet, so it slows down first. And these ones up here take the longest to slow down at the top of their arc up there wherever it is… <because> … they are the furthest away.

7.2.10.5 Vector probes

Anne correctly (and easily) interpreted the vector representations in these probes (this is consistent with her FCI scores for gravity (Table 7-31), and the NFC), but failed to recognise the inconsistency in her responses about the variation of force with distance (-N4) in the case of the planetary probes (Section 7.2.10.4).

71. also in the case of the multi-asteroid probes (transcript I:530)

72. as indicated by the FCI - see Table 7-32

7.2.11 Helen

Helen is undertaking a major study in both Mathematics and Drama, and a sub-major study in Physics. Helen's self-assessment of her knowledge of both Physics (in general), and the area of Mechanics in particular, were both 'good'. Helen's physics background is considered to be normal, with three years of studies in Physics completed, and additional studies in first-year Biology (Table A-13 on page 7).

7.2.11.1 FCI questions

The FCI data (Table 7-33) indicate that Helen has good understandings (>70%) of the NFC, although with some potential problems with N2 and N3. Her understanding of gravity (Table 7-34) (as measured by the FCI) shows good understanding of all three categories. Her FCI-predicted misconceptions (Table 7-35) shows a possible misconception (AF1) that only active agents exert force, and a number of potential[73] misconceptions in impetus, active force, and action-reaction pairs. Overall she appears as if she should be able to articulate appropriate Newtonian responses to most, if not all, of the probes.

Table 7-33: Helen - FCI results by category.

FCI category	0 Kinematics	1 N1	2 N2	3 N3	4 S-P	5 Kinds	TOTAL SCORE on FCI
Raw score	4	7	2	2	4	13	76%
Percentage	67%	88%	50%	50%	100%	81%	

73. nb. Hestenes' caution about single erroneous responses in a larger group of in-category items.

Table 7-34: Helen - FCI results for sub-category 5G - gravity.

FCI category	5G.1 Gravitation	5G.2 Acceleration	5G.1 Trajectory
Raw score	6	2	1
Percentage	100%	100%	50%

Table 7-35: Helen - predicted misconception areas[a] (after Hestenes et al., 1992, p.144).

Category	Details						
0. Kinematics	K1	K2	K3				
	×	×	×				
1. Impetus	I1	I2	I3	I4	I5		
	×	✓•	✓•	×	✓•		
2. Active Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7
	✓	×	×	×	×	✓•	×
3. Action/Reaction pairs	AR1	AR2					
	✓•	✓•					
4. Concatenation of influences	CI1	CI2	CI3				
	×	×	×				
5. Other influences on motion	CF	OB					
	×	×					
5.1 Resistance	R1	R2	R3				
	×	×	×				
5.2 Gravity	G1	G2	G3	G4	G5		
	×	×	×	×	×		

a. A '•' in a cell means that only one of a number of same-category misconception indicators was chosen.

7.2.11.2 Introductory questions

Consistent with her good FCI score, Helen demonstrates good understandings of gravity in these contexts. N4 is described as a general dependence on mass and distance, rather than the actual mathematical relationship.

7.2.11.2 (a) Gravity

Int:	What do you think of when you hear the word 'gravity'?	
Stu:	Um, I think of acceleration caused by the mass of two bodies - the force of attraction of two bodies.	s-/d- correctly identifies force between masses, but possibly sees acceleration as its defining effect?.
Int:	What can you tell me about gravity?	
Stu:	Only that it's different on different planets and on the moon, and depending on the mass of the bodies concerned, and the distances between the bodies.	s+/d- -N4

Int:	How do you think of gravity?	
Stu:	… it's the reason why things fall to the ground …why things with a mass fall to the ground.	s+/d-
Int:	Because?	
Stu:	Because they've got mass and there is a force of attraction between them. … I really wouldn't mention the word acceleration because you know it's not really something you can see automatically.	s+/d+ causal explanation possible PCK aspect?
Int:	Do you think of it as a force, or a field or what?	
Stu:	I think of it as an acceleration.	has acceleration as defining feature - not force (as above)
Int:	To describe it quantitatively, what would you say?	
Stu:	Well I think of the units; m/s^2, and … maybe working through the equation…the force between 2 bodies… forgotten it exactly, but it's something like the product of the masses divided by r^2…	s+/d- -N4 mathematical relationship given *without* gravitational constant.
Int:	What's your best example of gravity?	
Stu:	Oh, well if I was showing them <students> that it is an… an acceleration, we once did this thing where we connected it to a ticker timer, and then we could see you know the gaps were increasing.	s+/d- has acceleration as defining feature - not force (as above)?
Int:	Where do you find gravity?	
Stu:	Um… everywhere there are masses?	s+/d+
Int:	And how do you know if it is present?	
Stu:	Because things accelerate towards each other.	s+/d+

7.2.11.2 (b) Projectile probe

Int:	Do you think the motion is correct?	
Stu:	Well it looks to be correct.	-5G3 (FCI) does not detect incorrect diagram.
Stu:	It's moving towards the ring…so the distance portrayed in the picture … is the distance the same?	
Int:	Yes.	
Stu:	Well the velocity forward is constant, so if the component of the velocity that he has is broken into, that component, and the upward component, well… the up & down component …	

there's gravity which is causing it to … accelerating down, so for the first part of the motion, acceleration is in the opposite direction to the velocity, there, upwards – velocity, therefore it is slowing down, so that's why the gaps between them there is decreasing, and in this part the acceleration, g, is acting down, and the <vertical> gaps between the balls is getting bigger.	*+K0.5 (FCI) correctly resolves vertical and horizontal components.*
Int: And that's caused by gravity is it?	
Stu: Yeah.	*(no annotations to the diagram in the interview booklet)*

7.2.11.2 (c) Summary

Gravity is a force of attraction between two masses (+5G1) that causes them to accelerate towards each other (+N2), the magnitude of the force depends on their mass and distance apart in an unspecified manner (-N4). Projectile motion is due to the vertical acceleration (caused by gravity) of a body moving with a constant horizontal velocity component (+K0.5, +5G3 FCI).

7.2.11.3 Video Probes

Inertial events involving falling are wrong because the constant vertical force of gravity causes all objects to accelerate vertically at the same rate, but while Homer's trajectory is wrong for this reason, Wylie's is considered to be correct. The Ollie is considered unlikely because of N2 and N3 (+N2, +N3, +5G2 FCI).

7.2.11.3 (a) Homer's leap

Homer's acceleration down the slope is a result of a vertical gravitational force (l:216), and the leap is incorrect because gravity acts to make him fall from the moment he leaves the cliff (l:228):

> Yeah yeah there's just gravity acting on him, it's still… his um … the inertia of his movement is keeping him moving forwards. So he is continuing to move in that direction <horizontally>, but he's not accelerating in that direction. He's only accelerating down.

Helen uses N2 to explain why the Ollie is not possible (1:174), but is uncertain about the application of N3 (1:190):

Stu:	(1:174) The bit where he jumped off the skateboard, I don't think that's possible because as soon as he pushed down on the ... he pushed down on it as he jumped up, and it moved down a bit, but then it moved back up and he landed on it again. I think if he exerted a force on it, it's going,... it's going to increase its acceleration, and that's ... and they are still both going to falling at the acceleration of gravity, so he's not going to get back to it. Yeah.	s+/d+ +N2 +5G2 (FCI)
Stu:	(1:190) I am not sure if it's going to continue with this acceleration, or not – if its going to be momentary. So it's going to end up lower than him. Then they both just fall with the same acceleration So there is no reason why he is going to catch up with it.	uncertainty about impulsive vs. constant forces. +5G2 (FCI)
Int:	(1:199 ...he pushed down on the skateboard, and the skateboard has accelerated away for some indefinite period of time ...	
Stu:	Yep, there is also going to be ...a reaction force say if ... ah... so there must be, ... a force acting up on him, say...um yeah, I am not sure if you could do it or not.	+N3 Uncertainty if the magnitude of the reaction would explain the jump.

7.2.11.3 (b) Road runner probes

The different rates of falling depicted in these probes are judged to be incorrect because 'falling objects, no matter what their masses are, fall at the same *speed*[74], and they are all accelerating at the same acceleration' (1:135) because of gravity. In contrast to the Homer probe, and in apparent contradiction to the above, Helen states that the horizontal projectile motion off the cliff (probe 1.1) was correct[75] (1:96):

Int: But when he went off the cliff at the end, was that correct?... Horizontally?
Stu: Yes, that was correct.

74. i.e.. taken to mean that at any instant, they would have the same speed.

75. cf FCI gravity data for 'trajectory' in Table 7-34

She is confused about possible energy conversion in the impact scenario depicted in probe 2 (I:121):

Int: Can you give a summary reason why not?
Stu: Because he is accelerating towards the ground, and he would have to immediately …um slow himself right down completely even though he's travelling quite fast into the ground. And still have the energy stored in the bow from having it stretched out. Then when he hits the ground, he as to keep his body rigid so that he can, so that the energy is still in the bow, and then hold the bow in one position while he hits the ground.
Int: So you don't think the energy in the bow would have been transmitted to him?
Stu: No.

(Helen doubts the rebound is possible)
s-/d- NΘ - No discussion of impulse, momentum, or force. The notion of Wylie 'slowing himself down' makes no sense in Newtonian terms. At least might have expected a pseudo-Newtonian response such as … 'the bow does work on him (i.e. applies a force) to slow him and then accelerates him upwards' - before crashing into the ground?

7.2.11.4 Planetary computer probes

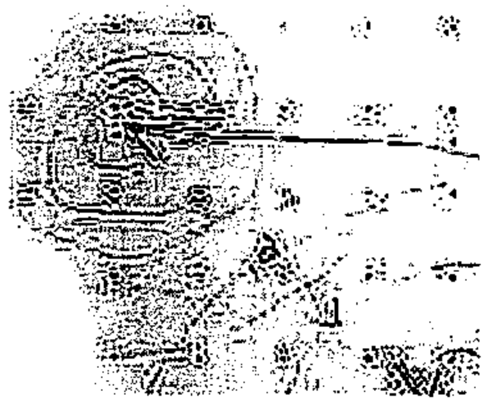
Helen determines that interplanetary gravity is the force between two masses (+5G1), and that gravity *around* a planet can be represented as a field of concentric circles of gravitational field strength that varies with distance from the planet in an unspecified manner (-N4). The asteroid's oscillation is caused by the superposition of force from the two planets, with the vertical components cancelling each other. Perturbations in asteroid orbits are due to both intra-asteroid and asteroid-planet gravitational forces.

7.2.11.4 (a) Single-planet probes

Helen correctly describes gravity as the force between the planet and asteroid (+5G1), and that the gravitational field around both of them can be represented by concentric circles depicting equal gravitational field strength[76] (which she refers to as *gravity*) that decreases with distance from the body.

76. i.e., GM/r^2 is constant along the perimeter of any particular circle.

Figure 7-38: Helen: gravitational field structures[a]



a. the grey artefacts are not part of the diagram, being caused by paper damage prior to scanning.

The resultant force on an object in the field is described, in scalar terms only, for an object located between the two masses (-S4.1). Table 7-38 shows the fields for each object — what the resultant field between them would look like is unclear.

7.2.11.4 (b) Dual-planet probes

The asteroid's motion in probe G4 is due to the horizontal[77] vector sum of the symmetrical forces from the two planets (+S4.1) which decrease with distance (1:422). The two vertical force components cancel each other as in Figure 7-39.

> Ah … this planet is going to be causing an acceleration towards it, and that planet's going to be causing an acceleration towards it, in equal and opposite directions since they are both the same mass. (1:422)

Figure 7-39: Helen: superposition of forces on the asteroid.

77. as in the diagram.

In subsequent probes, Helen was unable to provide a quantitative description of the relationship between mass, distance, and gravity (-N4), having already provided a rudimentary description in a previous response (Section 7.2.11.2 (a)).

7.2.11.4 (c) Multi-asteroid probes

Both intra-asteroid and asteroid-planet interactions are identified, with the former being held responsible for the fan-out in probe G7, and the latter for motion in G8 (in contrast to the clear description of the effect of distance in Section 7.2.11.4 (a)). The relationship or interactions between the two forces is not articulated, and there is no apparent basis for which acts 'most' (cf. CI1 FCI) in particular contexts. This may be due a difficulty in applying N4 to this context (despite having a good FCI score for gravity, a reasonable score for the NFC, and having stated the basis of N4 previously). Apparently N4 does not form the basis of a general gravitational model on which to base her responses[78].

7.2.11.5 Vector probes

Helen correctly interprets most of the vector representations of force, acceleration, and gravity in probes one to four, but is confused as to why the velocity and acceleration vectors are not colinear in probe three (Figure A-25) during orbital motion. In probe five, her apparent difficulty with N4 makes it hard for her to explain the rapid changes in the magnitude of gravitational force.

78. however, she was able to determine a reasonable field structure in Section 7.2.11.4 (a).

7.3 Field-dependence probes

Whereas it was anticipated that field-dependence might be significant in this thesis, no field-dependence effects were detected, with all of the participants being able to easily interpret the motion, although in idiosyncratic ways, depicted in both sets of the probes. Possible reasons for this finding are discussed in Section 7.3.3 below.

Table 7-36: Summary of responses to field-dependence probes. (Key: ✓ = gravity identified, X = gravity not identified, n/a = not attempted)

Participant	Visually clued probes[a]					Unclued probes[b]		
	1	2	3	4	5	Green	Blue	Red
1	✓	✓	✓	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓	✓	✓	✓
3	✓	✓	✓	✓	✓	✓	✓	n/a
4	✓	✓	✓	✓	✓	✓	✓	✓
5	✓	✓	✓	✓	✓	✓	✓	✓
6	✓	✓	✓	✓	✓	✓	✓	✓
7	✓	✓	✓	✓	✓	✓	✓	✓
8	✓	✓	✓	✓	✓	✓	✓	✓
9	✓	✓	✓	✓	✓	n/a	n/a	n/a
10	✓	✓	n/a	n/a	✓	✓	✓	✓
11	✓	✓	✓	✓	✓	n/a	n/a	n/a

a. on-line data entry (as on the CD-ROM).
b. some collected during the interview, and some subsequent to it using on-line data entry.

7.3.1 Unclued probes

These probes proved to be quite simple for most participants (cf. Chen, 1993), although their interpretations were as idiosyncratic— as with the series of probes in Section 7.2. The essential point, however, is that they were able to interpret the probes in the context of gravity, and explain their understandings. For the purposes of this thesis, as described previously, this is taken as meaning, for example, that the uniform motion in Green World was easily understood as representing a constant velocity (linear, with uniform spacing of dots - as in a ticker-timer tape). For example, Susan's responses to Green World:

Int: Well, can you see anything that looks like it's being caused by gravity? (1:469)
Stu: No, the lines are … they are all straight. The dots …are they supposed to be evenly spaced?
Int: Yes.
Stu: Well I think there is no gravity because they are not speeding up or slowing down.
Int: Why not?
Stu: The distance between them is always the same… um same distance per unit of time means a constant velocity sort of.
Int: Anything else?
Stu: Well there are no curves.

Jim, however, considered that the *absence* of a pair of 'interacting bodies' indicated the absence of gravity — perhaps related to his notion of gravity 'between' planets (see Section 7.2.5.2 (a)):

Stu: Ok, um…. No gravity! (1:486)
Int: Why not.
Stu: There is no two bodies to… interact?

In Blue World and Red World, curved particle motion was generally considered indicative of the presence of gravity, e.g., Susan's response about Blue World:

Stu: There is gravity there! (1:498)
Int: How can you tell?
Stu: Well… the line … the red line curves.

For most participants this was the most significant aspect of Blue World, with the linear acceleration noted, but the curved path attracted more comment, apparently being related, perhaps, to projectile motion. Curvature was also considered the defining feature in Red World e.g., Jim's response to Red World:

Int: What can you make of that? (1:520)
Stu: Well there is gravity there because all the particles are curving.
Int: So that's proof of gravity?
Stu: Yeah, the gravitational force always um… changes… ah…um bends their velocity vectors. I think we did one of those in the interview!

7.3.2 Clued Probes

In a similar fashion to the probes above, these probes presented little, if any, challenge to the participants — perhaps they were too similar to common physics depictions of ticker timer tapes or stroboscopic photographs of moving objects (cf. Chen, 1993). Curvature was again considered to be indicative of gravity, and the spacing of particles in the cube provided most participants with evidence of constant velocity (probes 1-3) or acceleration (probes 4 and 5). The explicit representation of the bounding cube appears to have focused participants' attention on events *inside* the cube, because most described the kinematic events without any consideration of what (outside of the cube) might have created a gravitational field in the space sampled by the cube.

7.3.3 Summary

Field dependence, as assessed by the probes used in this exploratory study, does not appear to be a factor in this study, as the participants were able to successfully relate events depicted in either format to gravitational contexts. This, however, may not be definitive as there is no clear mapping of this work onto, say, the traditional Group Embedded Figures Test (GEFT) instrument. These results are, however, consistent with related work by Chen (1993), Pirkle & Pallrand (1988), and Myers

(1997). Hein (1997) reports that while no significant relationship was found between students' learning style preferences and their ability to interpret (digital video) motion graphs[79], all students had difficulty when confronted with motions that deviated from what they had observed in the laboratory — as in this thesis when the participants were challenged by the events depicted in the probes which contained, perhaps, more contextual, real-world depictions than those in the somewhat formalised representations employed in the probes.

While no apparent field-dependence problems were detected in the participants' recognition and interpretation of the exploratory probes, this leads to several possible alternative conclusions. First, that these probes are 'too simple' visually for such problems to arise, or are not actually probing field-dependence. This is unlikely given that the clued probes are based on the proven 'rod and frame test' (Shipman & Shipman, 1985, p.233). Second, that they are too insensitive as an instrument — not being able to discriminate effectively between field-dependence and field-independence. There is no data to support a conclusion about this. Third, that the participants are, at least at the level of visual complexity embedded in these probes, all field independent. It is important to recall that the functional definition of field-dependence adopted for these exploratory probes (Section 6.4.1 on page 193) is that it relates to their ability to interact with the probes, or to make what is depicted meaningful to them (cf. Dwyer & Moore, 1991; MacKay, 2000, p.77). As all of the participants *were* able to articulate an idiosyncratic understanding[80] of the events depicted in them this may be likely. This is not to imply that results on

79. as measured by scores on the Test of Understanding Graphs-Kinematics.

80. though not all of which were correct Newtonian descriptions.

the GEFT would produce the same result, as there is no evidence to suggest that the probes and the GEFT do, in fact, measure the same things.

A possible explanation for these results may be that with the widespread use of computers in Education, the participants have indeed developed sufficient 'visual literacy' on computers to be able to interpret a range of complex graphic items such as those in the probes. Such speculation, however, requires quantification and validation, (which would form the basis of a subsequent study) to substantiate it.

7.4 The FCI as predictor

In the case of many of the participants, their responses to particular probes were contradictory to that predicted by the FCI, raising the issue of how useful the FCI actually is as a predictor of student knowledge in such contexts. In this regard, it has to be recognized at the outset that the FCI does not measure an individual's conceptual understandings, but rather, it is a measure of how closely the individual's understandings align with the NFC (Hestenes & Halloun, 1995b, p.502). Therefore, in circumstances which revolve largely around the NFC (as in this thesis), it is likely that there will be some correlation between the FCI score and performance in the specific context.

However, this has to be tempered by the fact that, as the data in this chapter shows, the FCI and the kinds of interactive probes employed in this thesis elicit quite different data, which are frequently inconsistent with each other. In any such usage, however, it is necessary to consider the nature of the alternative context, and how validly tasks performed there can relate to the pen-and-paper tasks in the FCI[81]. In essence this is an issue of 'kind' (cf. Keil, 1989, p.25) — whether the same *kinds* of things are being validly compared (or not). For example, in this study it has been demonstrated that, in a number of cases, dynamic representations and semi-structured probing elicits different data (nature and kind) than the FCI. Denise (Section 7.2.3 on page 265), for example, scored highly on the FCI (Table 7-9), with 100% for the gravity category (Table 7-10), implying that she should have little trouble with the relatively simple introductory questions and planetary probes. The opposite, however, is true, with Denise having considerable difficulty with the introductory questions (Section 7.2.3.2), demonstrating that she holds a model of gravity that is different from the Newtonian model, and possibly holds an active force misconception — not at all what one would expect from her FCI results. Similarly, Jim (Section 7.2.5 on page 281), who scores poorly on the FCI (Table 7-15), and particularly poorly on the gravity category, can provide a clear and accurate description of the action of gravity on a basketball undergoing projectile motion (Section 7.2.5.2 (b)). Whether these are issues of media (i.e., representational format), genre (i.e., verbal probing), or context (i.e., terrestrial and planetary events) is not clear in this study — but is an issue worthy of further examination in a subsequent study.

81. note that in this thesis, the FCI was used only as a general indicator of competence, and as a source of 'tags' for NFC-related items in the participants' transcripts (cf. Section 6.1.2 on page 176).

7.5 Conclusions

In terms of the research questions for this thesis (Section 2.6.3 on page 43), this chapter provides the basis for an answer to the first question: What is the nature of the participants' T-PCK and content knowledge of gravity in the VCE context?

7.5.1 Content knowledge

The data presented and discussed above clearly shows that the participants have, to varying degrees, fundamental deficiencies in their subject matter knowledge of the contexts examined in this chapter, and that, in most cases, they have great trouble in explaining the physics embedded in the probes, showing conceptual misunderstandings, inconsistent, and contradictory use of concepts and laws, unlinked and fragmented knowledge, and the presence of a significant number of misconceptions. I argue, therefore, that the data demonstrates that the participants, as 'learners', have not developed an adequate knowledge base (subject matter knowledge) about gravity and Newtonian mechanics, to be able to teach it correctly or effectively. The detailed nature of these problems have been described above for each participant, and are summarised below in Table 7-37 and Table 7-38.

Table 7-37 lists those participants who were able, on *at least* one occasion in the interview, to make correct use of Newton's or Kepler's laws; this does not necessarily imply that their understandings were consistently employed across the probes. In Table 7-37, it is particularly noteworthy how few participants made use of formal Newtonian arguments in explaining the events in the probes, relying instead on a mix of phenomenological arguments, general descriptive explanations

— sometimes with little actual physics content, and 'scientific' explanations that were not structured in a formal Newtonian manner. Some use was made of descriptions of underpinning mathematical models.

Table 7-37: Participants who *explicitly* demonstrated the correct use of the NFC, N4, or Kepler's laws on *at least one* occasion.

Law	Participant										
	1	2	3	4	5	6	7	8	9	10	11
Newton's first law (N1)				✓	✓						
Newton's second law (N2)				✓							✓
Newton's third law (N3)											✓
Law of universal gravitation (N4)							✓	✓	✓		
Kepler's laws of orbital motion											

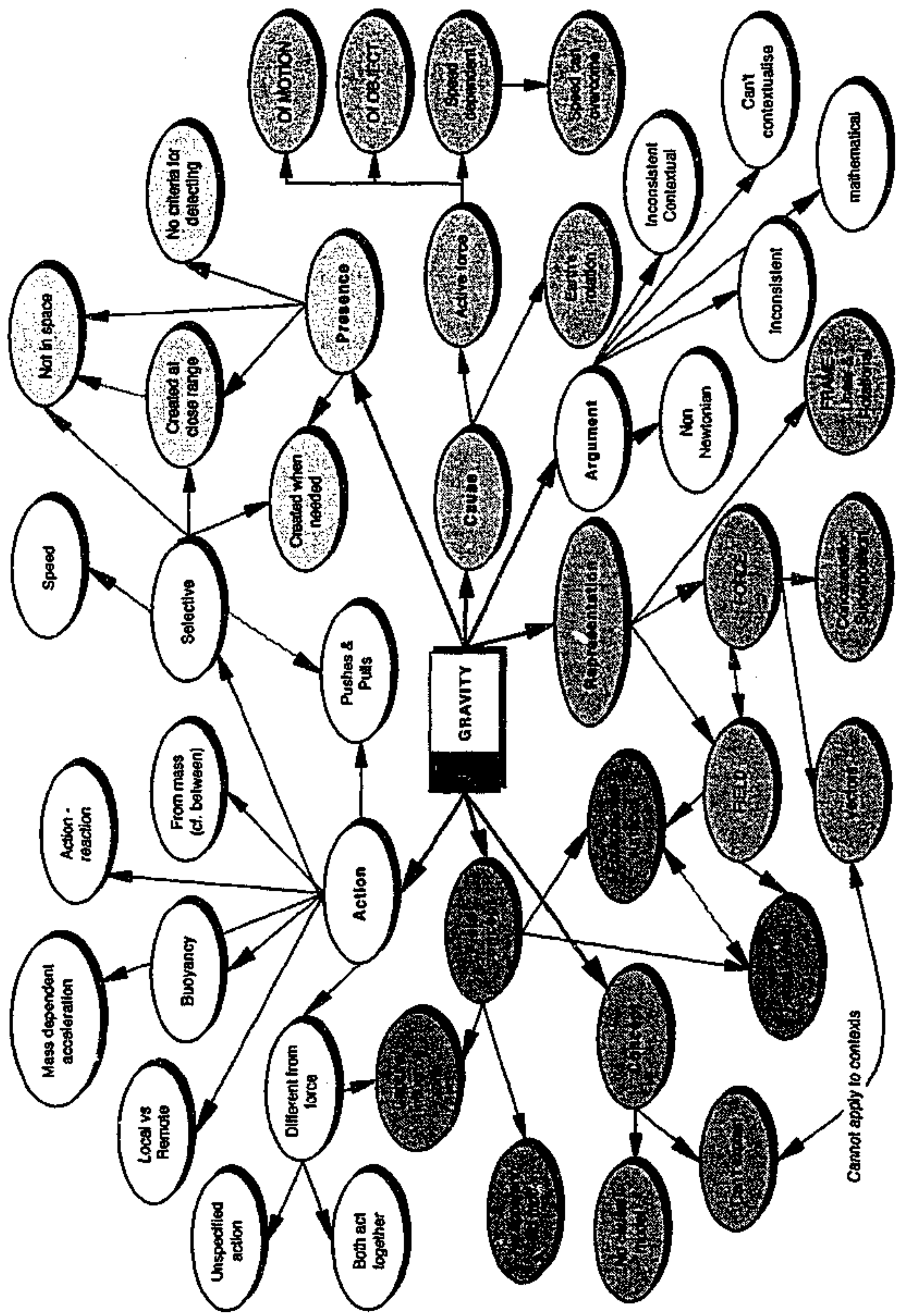
Table 7-38 on page 351 lists the participants' particular problems (identified on *at least one occasion* in the interview) with the probes. A potentially significant problem with Kepler's laws is evident, with Table 7-38[82] showing that it was not used in discussing the orbital probes, a surprising finding given their significance in 'explaining' the variation in orbital speed, and the elliptical orbits. Figure 7-40 shows this data presented, with some interpretation of links between categories, of the data in Table 7-38. The similarities and commonalities between Figure 7-40 and Figure 4-11 and Figure 4-17 are cause for serious concern, showing that the participants, as teachers, appear to hold the same kinds of misconceptions as their future students, which must cast doubt on their ability to both diagnose and remediate these in their students.

82. Continued on the following page

Table 7-38: Participants' specific difficulties gravity and the NFC (a tick in a cell indicates that at least one instance of a problem was detected).

Type of subject matter difficulty	Participant										
	1	2	3	4	5	6	7	8	9	10	11
Newton's first law (N1)	✓	✓	✓					✓			
Newton's second law (N2)		✓	✓	✓		✓	✓	✓	✓		
Newton's third law (N3)	✓						✓	✓	✓		
Newton's law of universal gravitation (N4)	✓	✓	✓	✓		✓		✓	✓	✓	✓
Kepler's laws of orbital motion - not used.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Kepler - circular orbits only										✓	
Concepts - nature and relationships		✓			✓	✓		✓			
Falling - rectilinear - rotational confusion			✓				✓				
Forces - concatenation or superposition	✓	✓						✓			
Gravity - concept: can't explain or apply.	✓	✓	✓	✓	✓	✓	✓	✓		✓	
Gravity - no causal model.	✓	✓	✓		✓						
Gravity - criteria for detection.	✓	✓	✓			✓					
Gravity: Representation and field structure					✓		✓	✓	✓	✓	
Gravity - no apparent 'field' concept.				✓							
Gravity - 'local' vs. between planets (confusion).					✓						
Gravity - force from a mass (cf. between).		✓	✓								
Gravity -action-reaction (Earth) or buoyancy.	✓	✓							✓		
Gravity - mass dependent acceleration.			✓		✓			✓			
Gravity - active agency of motion/active force.			✓								
Gravity - active agency of object/active force.		✓			✓				✓		
Gravity - different from force (both act together).	✓		✓		✓						
Gravity - different from force - unspecified.		✓	✓								
Gravity - capture or influence zone.				✓		✓					
Gravity - due to Earth's rotation.						✓					
Gravity - not in space.						✓		✓			
Gravity - selective action.				✓				✓	✓		
Gravity - selective - both pushes and pulls.	✓	✓									
Gravity - speed can overcome gravity		✓						✓			
Gravity - speed dependent (cf. active force).						✓		✓			
Gravity - created "when needed" at close range.				✓							
Argument - N0 - no use of formal Newtonian	✓	✓	✓	✓	✓	✓			✓	✓	
Argument - inability to contextualise	✓	✓	✓		✓						
Argument - inconsistent, contextualised			✓			✓		✓	✓	✓	
Argument - reliance on mathematical	✓										
Multiple realities - Newtonian vs Cartoon	✓										
Projectile motion - impetus								✓			
Projectile motion - constant accel. -> parabola											✓
Projectile motion-can't explain.	✓	✓									
Vectors - cannot apply vector concepts				✓	✓				✓		
Vectors - representation or interpretation	✓			✓	✓			✓			✓

Figure 7-40: Participant data represented in a similar format to those employed in Chapter 4 for misconceptions.



The majority of the problems depicted above are due to subject matter knowledge problems, but this should not be taken to mean that the representational aspects, and the participants' problems in explaining their understandings are any less significant or important for their long-term development as a teacher.

It is disappointing to find that this cohort of preservice science teachers holds many of the kinds of misconceptions about the NFC and gravity that were identified late last century in seminal works on student misconceptions — e.g., Champagne (1981), Clement (1982), Gunstone (1980; 1981), McCloskey (1982), Osborne (1981) Selman, (1982), Stead (1981), Stead and Osborne (1980), Vicentini-Missoni (1981), and Watts (1982). That the findings of this early research, and of the plethora of subsequent work on misconceptions[83], has apparently not made a significant impact on science education at school or university level[84] is both tragic and symptomatic of the issues that led to Cochran and Jones' (1998, p.707) concerns about the lack of focus on preservice science teachers' subject matter knowledge in preservice teacher education courses (cf. Dykstra Jr, 2000).

Indeed, Hestenes' call for a software curriculum is implicitly grounded in the apparent failure of several decades of science-education research to have a wide-scale impact on contemporary practice. Whether Hestenes' proposal is a naive, technocentric one (Papert, 1987), or one that is based incisively on the perceived potential of computer-based technologies to invigorate and transform science teaching (e.g., Andaloro & Bellomonte, 1998; Dede et al., 1996) is unclear. However, by articulating aspects of it (ubiquitous, integrated use etc.), he attempts

83. e.g., as exemplified by the three Cornell conferences on misconceptions (e.g., Novak, 1993), and Duitt's misconception bibliography (Duit & Pfundt, 2000).

84. i.e, in the context of the participants of this thesis.

to define a coherent rationale for science education that implicitly incorporates radically different pedagogical models than those currently routinely found in schools[85]. Perhaps, should his vision come true, the implicit centrality of pedagogy may, indeed, lead to the kinds of outcomes he envisages for science learners.

In the case of the participants of this study, there are serious questions to be asked about the nature of their physics[86] program, particularly about the ways in which it is taught and assessed. Similarly, their apparent difficulties in creating and articulating valid representations of their subject matter knowledge also needs detailed examination, but in both faculties (Science and Education), as there is little evidence of developing or emerging T-PCK in the data.

7.5.2 PCK

Arguably, the participants' use of diagrams to explicate their responses in Section 7.2 might be regarded as T-PCK in the form of representations of their understandings (cf. Section 3.2.1 on page 62). However, because these were generally incorrect[87], or often took the form of standard textbook representations, these have not been regarded as being examples of T-PCK because they are *not* focused on an adaptive, contextually sensitive, explication of content, but rather, were attempting to define their understandings of the events in the probes. This is a subtle distinction, but one that is supported by the PCK literature, where researchers do not normally consider 'routine' presentation of subject matter knowledge to be

85. cf. Songer's (1998, p.335) articulation for developing scientific content knowledge.
86. i.e., for physics subject matter knowledge development.
87. i.e., were incorrect depictions of Newtonian concepts, or contained non-Newtonian entities (or argued for them).

PCK — if it were, then much of the current difficulty that educational researchers have in identifying instances of T-PCK would disappear.

As the focus of this thesis, the lack of evidence of T-PCK i.e., representations[88], is disappointing, yet illuminating, leading to several possible conclusions. The first is that the absence of *effective* representation (and associated argument) can be taken as evidence of a lack of T-PCK in the participants. The second is that the methodology employed was neither sensitive nor effective in eliciting examples of T-PCK. However, I argue that because the data shows evidence of the participants producing content representations (while noting the argument presented above), the methodology is, prima facie, capable of eliciting the desired *kinds* of representational data.

The implications of a poor or inadequate subject matter knowledge base for the participants as 'teachers' are profound — since, in both Shulman's original model of PCK (Figure 3-2 on page 49), and Magnusson, Krajcik and Borkos' model of PCK for science teaching (1999) (Figure 3-3 on page 51), a fundamental aspect of PCK is about, '...ways of representing the subject to make it comprehensible to others.' (Shulman, 1986b, p.9) In the case of T-PCK, as is considered in this thesis, it is about teachers' abilities to interpret, explain, contextualise, simplify, or represent subject matter knowledge in ways that make it accessible to students (Magnusson et al., 1999, p.111). However, it is implicit in this definition that these must be based on, and originate in, a high level of understanding of the relevant subject matter knowledge, and not on misconceptions, or a lack of understanding of

88. as defined in Section 3.2 on page 61.

subject matter knowledge. I argue that some of the participants' explanations above are salient testament to this position, and present some examples (not to be regarded as an exhaustive list) below in support of this argument.

Table 7-39: Educational implications of explanations based on, or indicating, erroneous understanding of physics content knowledge.

Participant	Example	Implications for teaching
Joanna	In Section 7.2.1.4 (b) on page 254, she describes a force acting to attract the asteroid to the planets, but is not sure if this attractive force is simply 'a force', or if it is gravity. This force both pulls and pushes on the asteroid at different times.	Gravity is an *attractive* force between masses. Exposing learners to Joanna's idea would cause fundamental confusion about the nature and action of gravity, particularly in regard to N4 and action-reaction forces.
Susan	Susan describes gravity in terms of active agency by the planet which 'tries to pull back the asteroid ... making it do what it wants it to do' (See Section 7.2.2.4 (a) on page 262).	Negates the mathematical and abstract models of Newtonian mechanics by suggesting to students that objects can choose how and when to exert their gravity, or are affected by it - contradictory to the NFC.
Denise	Denise explains the parabolic curve that characterises projectile motion as being due to '...the motion pulling it <a ball> to the ground' (See Section 7.2.3.2 (b) on page 267)	This suggests that the motion is the result of an 'active force', which is contrary to the NFC, and would cause students to see the motion of objects as due to a force *from* the motion, rather than the motion being the result of forces acting *on* an object.
Alex	Alex describes gravity as 'always existing' yet is created when objects are brought close together. (See Section 7.2.4.4 (a) on page 278)	An inconsistent argument that contradicts N4. The notion of gravity suddenly being created at close range could cause students to have great difficulty explaining or understanding field concepts and N4.
Jim	Jim explains that projectile motion is due to the vector sum of momentum and the force of gravity. (See Section 7.2.5.3 (a) on page 284)	Any attempt to have students add vectors of different types could lead to wide scale confusion about representing any mechanics context in vector form.
Joe	Joe explains that there is no gravity outside the atmosphere because it is something to do with the Earth. (See Section 7.2.6.2 (a) on page 292.)	Completely inconsistent with the Newtonian model. Its use could result in students not only having conceptual difficulties with N4, but also lead to the development of the Aristotelian dichotomy between terrestrial and 'heavenly' motion (Section 4.2.2 on page 83).

Table 7-39: Educational implications of explanations based on, or indicating, erroneous understanding of physics content knowledge.

James	James relates projectile motion to orbital motion, juxtaposing linear and rotational frames of reference. (See Section 7.2.7.3 (a) on page 300)	While this can be done (see Figure 4-15 on page 125), it requires a precise articulation of the argument if students are not to be confused about how to describe and analyse rectilinear motion.
Steve	Steve explains that projectile motion shows that the force of gravity on the ball increases as the ball slows down. (Section 7.2.8.2 (b) on page 310)	This suggests the selective action of gravity causes acceleration, which contradicts the NFC and suggests agency - confuses students about 'what is acting on what'.
Alan	In explaining the superposition of forces from two planets on an asteroid (Figure 7-33), Alan draws force vectors that always connect the asteroid to the planet, and then argues that this shows that gravity increases with distance from the planet.	This incorrect representational form will lead to fundamental confusion over using vectors in diagrams. Students need to understand that it is not necessary to connect the entities - development of mathematical and graphic skills in scaling are needed to overcome this approach.
Anne	Anne explains that all orbits are circular. (See Section 7.2.10.4 on page 331).	Generalisation from a single case will lead to severe problems with Kepler's laws, and understanding why orbits can be elliptical.

These examples show the importance of teachers having a good subject matter knowledge, and the educational implications of their failure to acquire such knowledge. In the case of preservice educators (as in this thesis), there is a strong case to be made that explicit attempts to develop their PCK should occur concurrently with their content knowledge, especially given that the development of pedagogical content knowledge is a long term process (Zembal-Saul et al., 1999, p.243). The data presented in this chapter demonstrate the immense difficulties that the participants had in making clear and effective representations (both graphic and verbal) of their subject matter knowledge of gravity and the NFC — and they are fourth year science students with extended periods of teaching science in schools in the three years prior to, and including, the research interviews. The lack of obvious

PCK, demonstrates, in the case of the participants at least, that PCK does not develop spontaneously from subject matter knowledge, and so presumably must be explicitly developed in preservice teacher education courses. Chapter 8 takes up this issue by focusing on the concurrent development of PCK and subject matter knowledge in a PCK-enhanced software environment (as described in Chapter 1).

7.6 Chapter Review

This chapter describes and examines the participants' responses to the interview probes by means of a semantic content analysis that relates them to the Newtonian Force Concept, and gravity, in the context of the VCE physics curriculum[89]. The use of annotations and side-by-side analysis and data-presentation is an attempt to meet Lythcott and Duschls' (1990) concerns about the need to provide defensible claims by creating a transparent and reconstructible semantic analysis of the data. The use of the FCI as a predictor of performance on other instruments is reviewed in the light of the data presented in this chapter, and the implications of the lack of any apparent field dependence on the use of the probes is discussed. Participants were found to have fundamental conceptual difficulties with the NFC, to hold a range of common misconceptions, and to have great difficulty in representing and explaining their understandings of the gravitational contexts employed in this chapter.

89. See "VCE Physics Unit 4, Area 2, details." on page 1.

Chapter 8

Principles for the conceptual design of PCK-enhanced software

8

Principles for the conceptual design of PCK-enhanced software

> Perhaps, because representing expertise is so challenging, much effort has been put into building intelligent tutoring systems, that have deep or expert system representations, but relatively little effort has been put into exploring the knowledge that is needed for teaching.
>
> (Murray, 1996, p.235)

8.1 Introduction

This chapter addresses the second research question (Section 2.6.3 on page 43): What is the nature of a pedagogical knowledge-base (for teaching part of the VCE physics curriculum) that could inform the development of software (i.e., PCK-enhanced software) that could be constructed to support and facilitate the development of both T-PCK and content knowledge in this area of the VCE curriculum?

It is important to note that the focus here is on articulating *principles* that can inform the development of PCK-enhanced software (see Section 1.1 on page 1) that might address the kinds of conceptual and pedagogical concerns identified in the participating preservice teachers, i.e., a data-driven approach. This is a very different task from that of developing a definitive general pedagogical knowledge base (cf. Zembal-Saul et al., 1999), or a comprehensive list of knowledge and skills for teaching Newtonian mechanics, because it aims to be both data-driven, i.e., based on the participants' responses, and limited to the narrow confines of the VCE unit 4 gravity context (Section A.1), and to focus mainly on those aspects of significance for software design. This is not to imply that this chapter aims to develop a sparse, selective knowledge base. Rather, issues related to categories outside of those examined herein (as in Figure 1-1 on page 6) are implicit, but are neither explicitly addressed nor articulated here — but they are considered to be included as essential, but unarticulated, aspects of the pedagogical (and subject matter) knowledge base.

A fundamental issue in articulating principles to inform the design of PCK-enhanced software, and the nature of the associated knowledge bases, is how the relationship between subject matter knowledge and PCK is to be structured. Is it adequate to graft PCK aspects on to existing science concept learning software such as SemNet (Fischer, 1990), or related conceptual mapping, exploration, and visualisation tools such as CoVis (Gomez, Edelson, & Fishman, 1997), MaxWell World (Dede et al., 1996), SenseMaker (Linn & Hsi, 1998), WISE (Linn & Hsi, 2000), and TurboTurtle (Cockburn & Greenberg, 1995), or is a new class or genre of educational software required in order to accommodate Hestenes' implied demands? The answer to this question is neither simple nor obvious, demanding the careful consideration of the nature and role of PCK in a software environment — as is conducted below. For example, with the increasing incorporation of pedagogical agents[1] into a range of software types, it is possible to foresee that they could also be incorporated into a wide range of existing educational software (although this seems contrary to Hestenes' position). However, how effective use could be made of their existence in terms of their linking of PCK and content knowledge is perhaps problematic, as much conceptual development or modelling software is not necessarily created with pedagogical aspects as a central feature of their design. Rather they are commonly designed around specific cognitive or domain models. This is not to say that they could not be redesigned to accommodate such features, but in doing so, I would argue, a new genre of software would be created. I prefer to regard the kind of software environments that Hestenes envisages as a genre that needs to be considered afresh, without building on the legacy of any particular stand-alone software — a position that Hestenes explicitly expounds (Hestenes, 1995, p.64). In this chapter, the nature of such a genre is explored from a software development perspective (as opposed to a 'conceptual' perspective in which psychological paradigms dominate the design[2]) in order to attempt to articulate some of the defining features of PCK-enhanced software. This task, as discussed in Section 1.2 on page 5, is a small step along the path to developing an informed understanding of Hestenes' seductive, but ill-defined, notion of how science education could be transformed through the use of technology.

Section 8.2 examines how PCK may be incorporated into software environments that could form the basis of a PCK-enhanced software design. Section 8.3 examines the implications and issues arising from the data in regard to software development — as ways of addressing those issues, and the features that might need to be incorporated into PCK-enhanced software in order to accommodate them.

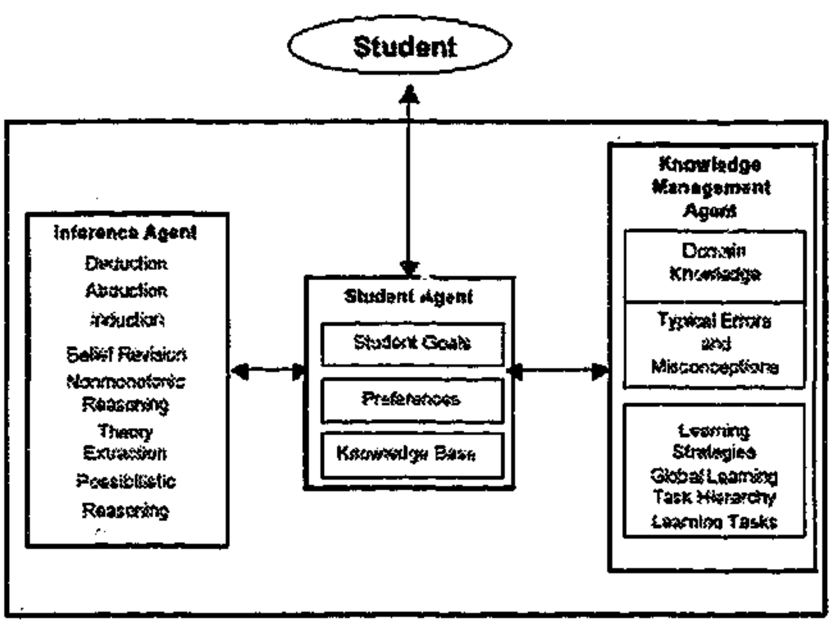
1. software that implements intelligent (in the context of the Artificial Intelligence literature), contextually sensitive, monitoring of user activity, and provides actions (messages, procedures) in response. Pedagogical agents are generally defined as those that provide the user with guidance in the completion of a specific task. The 'Assistant' built into Microsoft Word 2000 is an example of a software agent.

2. cf. SemNet (Fischer, 1990), Boxer (diSessa & Abelson, 1986), and Logo (Abelson, 1984).

8.2 Software considerations

This section discusses the likely nature of a software 'engine' that could act as the kernel of a PCK-enhanced software environment in which to implement an appropriate knowledge base. A starting point for considering this is depicted in Figure 8-1 — a contemporary design for an agent-based[3], adaptive[4], intelligent[5] tutoring system (Bruff & Williams, 2000) for developing learners' *subject matter knowledge* (cf. Murray, 1990; 1996).

Figure 8-1: Agent-based, adaptive, knowledge base structure focusing on developing subject matter knowledge. (Bruff & Williams, 2000)



This model is used here to illustrate important aspects of knowledge base development in software, not as a definitive solution. In this design, as with most data-driven software, the knowledge base that informs its actions forms a critical,

3. see Genesereth (1994).
4. i.e., modifies it's behaviour in response to user input.
5. i.e., based on artificial intelligence architectures such as expert systems and neural nets.

intimate, and evolving, part of the software, and needs to be considered as integral to it, and not as something that stands outside of it[6].

This design has been chosen from a plethora of alternative software architectures, not because it is intrinsically the 'best' (but it *is* a very good model — as explained below), but rather because it is both simple[7], allowing (with minor changes) the incorporation of the findings of this thesis, and exemplifies features that appear to be useful in the inclusion of aspects of PCK in software — *agents* (e.g., Foner, 1993; Genesereth & Ketchpel, 1994), and *automated knowledge acquisition* in response to user actions. The reasons that these are important aspects of PCK-enhanced software are discussed below, before addressing the items depicted in Figure 8-1, and the nature of changes that might be needed to accommodate PCK in such a model.

8.2.1 Agents

Software agents are an important aspect of contemporary software design as they facilitate the development of software in which normally static entities (such as database tables — e.g., rules about knowledge) are (effectively) enabled by intelligent, contextually aware, communication processes in order to provide, for example[8], an appropriate contextual response rather than a preprogrammed response to a particular event. In *effect*, they are a software instantiation of Lawler's conformal and coordinating microviews (Figure 3-7 on page 59), hence their

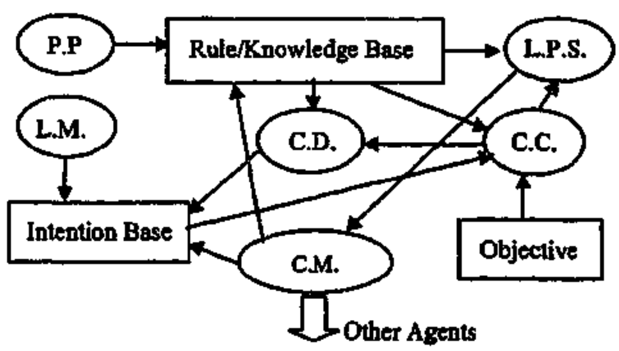
6. although the specifications of the knowledge base are normally developed externally before being implemented in software.

7. at the general level shown in Figure 8-1.

8. software agents are widely applied in diverse roles.

obvious relevance to this thesis. Examples of 'simple[9]' pedagogical agents can be found in common software such as the 'Assistant' in Microsoft Office (Microsoft, 20001). Agents are complex, data-driven software objects[10], that act in accordance with the knowledge, and rules about the use of that knowledge, that are programmed into them. Figure 8-2 shows the typical complex structure[11] of an agent that is intended to work cooperatively with other agents (Yang, Wang, Qu, & Dong, 2000, p.1). The complexity in these agents stems from the need for them to engage in autonomous interactions with other agents and external users (i.e., people). Why this feature is so useful for PCK is discussed below in Section 8.2.3.

Figure 8-2: Typical internal architecture of a software agent (Yang et al., 2000, p.1)



When an agent's role is to 'instruct' or 'advise' users (explicitly or implicitly) about their current or deduced course of action, such agents are commonly termed 'pedagogical agents' (Johnson, Shaw, & Ganeshan, 1998). Additionally, pedagogical agents with 'personality' are often represented graphically as avatars[12] (Figure 8-3). Being an avatar is not an essential attribute of a pedagogical agent.

9. i.e., agents that do not have to cooperate with other pedagogical agents.
10. i.e., collections of software elements as in Figure 8-2.
11. KEY: partial perception (P.P), learning mechanism (L.M),communication mechanism (C.M.), coordination control (C.C.), collision detection (C.D.), and local problem solving (L.P.S.)
12. a Sanskrit term loosely meaning a self-representation.

Avatars are often used in a human-computer interface role to advise users about the operation of automated tasks that fulfil a specific organisational role — (as depicted in Figure 8-3).

Figure 8-3: Example of a simple, non-interactive, email pedagogical agent incorporating an avatar. (Holkner, 2000)

'Adele' (CARTE, 1998) is a classic example of a pedagogical agent of the type of interest here, being employed to bring about curriculum reform in medical education by providing medical and dental students with more authentic diagnostic skill development experiences (Shaw, Ganeshan, Johnson, & Millar, 1999).

Figure 8-4: Adele: clinical 'discussion' with an avatar (CARTE, 1998).

> Simulations created for the course in diagnostic skill development will present the physician/student with actual cases, including patient history, results of exams, lab tests, x-rays, CT scans and other diagnostic imagine methods. By questioning and examining the virtual "patient" and studying clinical data, the student will be able to practice diagnostic skills. Adele will provide feedback and a review of the student's progress, referencing diagnostic best-practice, and cost-analysis criteria. (CARTE, 1998).

Additionally, Adele is 'Internet enabled', allowing collaboration, discussion, and reflection with learners in both local (i.e., classroom teaching) and distributed (i.e., distance education) modes.

In the context of this thesis, it is easy to see how such software could be adapted to both classroom pedagogical processes (and PCK), and the development of subject matter knowledge. In the former case, imagine a classroom incident being presented, in which the teacher has to determine the most appropriate discipline strategy. Several avatars could appear, each arguing for the use of a different discipline model, with the teacher having to choose the most appropriate model (and receiving feedback after making a choice). Alternatively, as an exercise in developing T-PCK, a student teacher might be asked to explain a science experiment to students, and in a similar way to the above, several (avatar) teachers appear to provide advice, with the student teacher being required to both choose and justify the approach taken. In terms of subject matter knowledge, most current instructional systems diagnose incorrect responses — for example, misconceptions[13] (cf. Figure 8-1), but do not commonly provide advice about their possible cognitive origins. Pedagogical agents are rarely, if at all, used in such software, but could be incorporated to provide such feedback. In a similar way to

13. Murray's 'buggy knowledge' (Murray, 1996).

the above, having a discussion with (an avatar) Aristotle or Newton (or a teacher), or being able to 'listen' to a projectile describing its changing variables as it moves, (and receiving feedback in each case) might be a powerful learning experience through the direct experience, feedback, and the possibility of subsequent metacognitve reflection (cf. Baird, 1998, p.159-65; Gunstone & Northfield, 1994) — something that some existing pedagogical agents have already been developed to do! (e.g., Baylor, 2000; Rutz & Tholander, 1999)

8.2.2 Adaptivity: automated knowledge acquisition

The use of agency alone is only adequate for providing learners with appropriate contextual responses over time if the knowledge base used for such responses is static, clearly defined, and carefully delimited. For example, the rules of clinical diagnosis embedded in Adele would not be expected to change significantly over time, with particular symptoms presumably eliciting a particular diagnosis, though Schroder et. al. (1996, p.60), note that this is, however, quite a difficult reasoning and problem-solving task. In the case of Education, the situation is not so clearly defined, with teachers, including preservice teachers, developing changing, contextual, and situative understandings (e.g., Putnam & Borko, 2000), that both arise from, and impact on, their practice, i.e., there is no fixed 'diagnostic database' to provide teachers with 'the answer' to apply in response to a particular event — indeed this is the essence of Shulman's notion of PCK.

The implication of this for implementing PCK in educational software is profound — that the knowledge base must evolve and adapt with the users' (i.e., student teachers) understandings. In a similar fashion to that in which clear examples of PCK continues to elude researchers, creating and representing instances of PCK in software may prove equally challenging. Bruff and Williams (2000), however, have addressed some of these concerns by focusing the development of knowledge base architecture (Figure 8-1) around students, and their beliefs, desires, and intents — the BDI (Beliefs, Desires and Intents[14]) model (Rao & Georgeff, 1988):

> In essence our intelligent tutoring system builds and maintains a student model in a dynamic learning environment where new, possibly inconsistent or uncertain, information is obtained through interactions with the student, and where the system may not have complete knowledge when deciding on the next instructional step. Our architecture supports the development of highly individualised student models using techniques in belief revision, nonmonotonic reasoning and possibility theory. (Bruff & Williams, 2000, p.1)

Designing software in this way, rather than around domain structures (e.g., Newtonian mechanics), facilitates the development of a student agent that keeps track of the users' (perceived) 'beliefs, desires, and intents' in regard to learning (history, state, and difficulties); information that the knowledge management agent can make use of in deciding on the selection of content for a particular user at a particular time.

8.2.3 Accommodating PCK in software

The inclusion of adaptivity, as above, is the second essential precursor[15] to accommodating meaningful depictions of PCK in software environments such as those envisaged by Hestenes. It allows for both the incorporation of pre-existing PCK data, as gleaned from teachers and other sources (as in this thesis) (cf. Jiao &

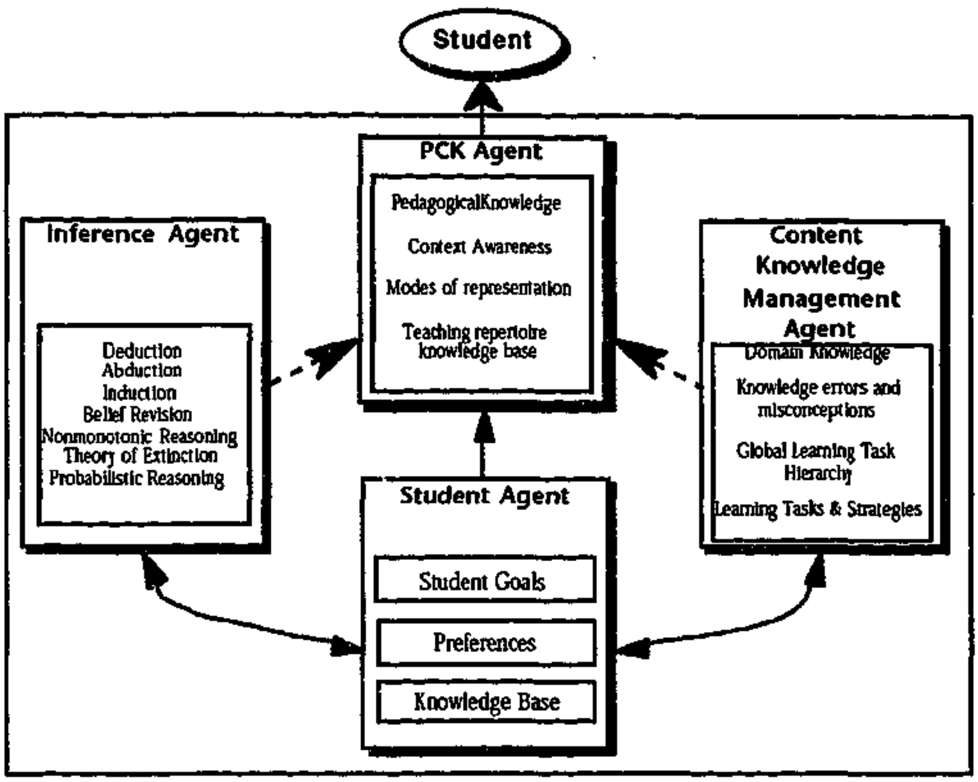
14. an animistic metaphor to describe the structure of a user's interaction with the system.

15. Agency was the first.

Shi, 2000), and the incremental development of personal aspects of PCK by the learner (i.e., preservice teachers) over time, which contributes, iteratively, to the development of the PCK knowledge base (as discussed below). As a software engineering construct, PCK presents a host of challenges to designers because of it's fuzzy nature (cf. Nicholson & White, 2000a), which does not fit easily into a carefully defined knowledge base ontology (cf. Murray, 1996), it's complex structure (e.g., Magnusson et al., 1999) which makes it harder to represent in software, and it's cross-domain nature (e.g., Morine-Dershimer & Kent, 1999) which appears to require particular attention to linkages across knowledge bases.

At one level it is tempting to include PCK as part of Bruff and Williams' knowledge management agent (Figure 8-1), because it relates to both learning strategies and content knowledge. However, the model of PCK for science teaching (Magnusson et al., 1999) described previously (Figure 3-3 on page 51) has both a complex structure, and a focus different from, but related to, subject matter knowledge. Arguably the T-PCK component (as examined in this thesis) might sit within the learning strategies category, but this would presumably separate it from other elements of PCK. It therefore seems reasonable, given that PCK is a new, ill-defined, and apparently complex, entity in this context, to consider it's implementation as a fourth agent category in Bruff and Williams' model. This is more than semantics; the unique and comprehensive nature of PCK does not sit easily in structures developed 'in ignorance' of it. The implications of this, at a conceptual level (in terms of Bruff and Williams' model) is that the PCK agent would (conceptually) mediate the interactions of the knowledge management agent with the student agent and inference agent as depicted in Figure 8-5 — which attempts to present a 'comprehensible visible metaphor' (Harper, Hedberg, Wright, & Corderoy, 1996, p.416) for how the agents might be related[16].

Figure 8-5: Suggested incorporation of PCK into Bruff and Williams' intelligent tutoring agent model. (adapted from Bruff & Williams, 2000)

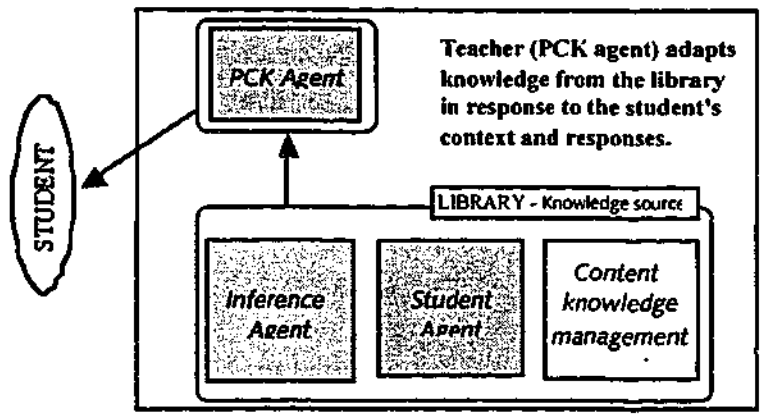


In this proposed modification to Bruff and Williams' software architecture, the PCK agent effectively mediates 'decisions' and processes that are made by the other agents (on the basis of their cognitive models and subject matter knowledge), in a similar manner to that which teachers' PCK presumably filters and modifies their subject matter knowledge to produce appropriate contextual and temporal representations of it for their students. Perhaps an appropriate analogy for this structure is that of a teacher (PCK agent) and a 'subject matter library' (comprised

16. It may, or may not, be appropriate to relocate the learning strategies component of the knowledge management agent into the PCK agent, depending on the specific nature of each.

of the other three agents) that provides the teacher with the content for teaching, as in Figure 8-6, who then adapts it to meet the needs of students.

Figure 8-6: *Teacher-library metaphor for the relationship between the components of Figure 8-5.*

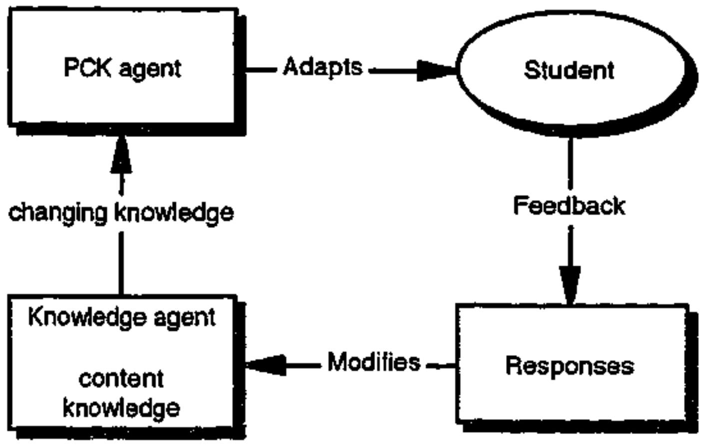


This model has the advantages (particularly for software design and engineering) of leaving the existing knowledge bases, agents, and inter-agent processes intact, which means that they can continue to function without regard to pedagogical aspects, preserving their knowledge and inference structures[17], and allowing a variety of alternative PCK models to be implemented by 'simply' replacing one PCK agent with another (although the development of such PCK agents is not likely to be an easy task). The links (in Figure 8-5) *to* the PCK agent from the inference and knowledge management agents imply that the PCK agent will, itself, need to be self-modifying (adaptive), learning to adapt as the student's[18] subject matter knowledge and 'thinking' processes improve over time as part of the reciprocal relationship between PCK and subject matter knowledge, as shown in Figure 8-7 below.

17. the data and the rules and methods that operate on them (cf. Lawler, 1985)

18. i.e., on an individual basis for each and every user.

Figure 8-7: Mutually adaptive relationship between PCK and content knowledge.



In regards to the data collected in this thesis, this arguably implies that, in such a system, the explanatory and representational difficulties that the participants displayed, could be addressed at the pedagogical level through the development of appropriate pedagogical experiences and strategies (as discussed below), with fundamental subject matter knowledge deficiencies (and associated misconceptions) being dealt with by the content knowledge management system agent alone, which is 'aware' of common learning difficulties and misconceptions (i.e., in the case of this model — see Figure 8-1). This mutually adaptive relationship (Figure 8-7) should ensure the gradual, iterative, improvement in both content knowledge and PCK[19]. This is a very attractive proposition from a software engineering perspective, as both knowledge bases 'feed off each other', without having to incorporate explicit links between them (i.e., it facilitates the decoupling of the PCK agent from the subject matter agent). For example, the content knowledge agent could continue to act in conjunction with the student agent to try to improve a user's understanding of Newton's first law, without having to be

19. it is expected that routine diagnostic procedures would alert supervisors to cases where there was little, or even regressive, change.

concerned about what sort of representations of it were being produced by the PCK agent (which would, however, be aware of how the learner responded to different types of representations). However, there is obviously a need to ensure that the two agents work together to improve learning, rather than simply acting in ignorance of each other, hoping for a serendipitous outcome. In traditional (non-agent) software architectures, this would presumably require strong (hard-coded) linkages between the competing components. However, in an agent-based system, the agent (cf. teacher) has simply got to get better at performing it's tasks correctly — which is why it has to be adaptive. In effect, over time, the feedback from the user and the knowledge management system will allow the PCK agent to be a better agent — in a disturbingly similar way to that in which science teachers (hopefully) develop expertise with increasing classroom experience.

For example, in the case of Jim (Section 7.2.5 on page 281), his confusion over the action of gravity (he depicts both gravity and a force acting together — apparently gravity and force are different in his mind), might need to be addressed by both the PCK and content knowledge agents. First, there is a need to ensure that Jim understands, and can apply N4 to planetary gravity, and can discriminate between local and planetary gravity (he may already be able to do this) — a task for the content knowledge agent. However, as the data show, despite having subject matter knowledge, he may still be uncertain about how to represent or explain it (e.g., Figure 7-14 on page 284), hence the need for the PCK agent to employ a variety of representational forms that helps Jim to understand that the force he is representing is, in fact, gravity. The roles of the agents, while mutually supportive, are quite different.

Similarly, Steve's difficulty in representing a field structure (Figure 7-30 on page 315), could presumably be improved, for example, by presenting a series of representations such as graphs of 'g versus $1/r^2$', and diagrams similar to James' field picture (Figure 7-23 on page 303). Subsequent representations could use multimedia or Java applets to provide representations similar to those used in the vector probes (Section 6.4.4.3 on page 235). Whichever representational form is used would be selected (by the PCK agent) on the basis of the subject matter being fed to it, *and* it's interpretation of Steve's responses to previous (if any) representations. Whether the incorporation of avatars into this system would enhance it is unclear, as there is no implicit human-interface model in this design, although if implemented in a similar fashion to Adele, then they would probably be advantageous if they were able to support the user's active engagement and interaction with the software.

The deliberations above have led to one apparently important design principle for PCK-enhanced software — that there are advantages in implementing 'PCK' as an actor with a similar role to that of a classroom teacher, and not to intertwine it with subject matter systems. How readily this can be done depends, as Murray notes at the start of this chapter, on how easily the expertise embedded in PCK can be understood and interpreted (and implemented) in ways that can inform the development of the knowledge bases that are central to agents' functionality. The following section attempts to tease out some of those elements in the context of the microcosm of this issue that is explored in this thesis — not as expertise, but as ways of overcoming cognitive and pedagogical problems that hinder it's development.

8.3 Lessons from the data

This section focuses on addressing research question two from a data-driven perspective by considering what the data presented in Chapter 7 implies for the attributes of a pedagogical knowledge-base that would underpin software design — what are the types of entities that the data suggests might be included[20] in the development of a pedagogical knowledge base, and how could these be incorporated in software? As discussed in Section 7.5, two fundamental issues stand out in the data[21], each of which is examined below:

1. the apparent lack of basic subject matter knowledge (and an associated inability to consistently apply, contextualise, or articulate it);
2. the lack of indication of emerging T-PCK.

In terms of the goals of this thesis, the nature of the participants' subject matter knowledge has already been described in Section 7.5 on page 349. In this section, however, those problems (while being 'subject matter' problems rather than pedagogical concerns) are described below in a way that attempts to facilitate their being addressed through the interaction between the PCK and knowledge management agents (as in Figure 8-5), in a somewhat similar way to that in which Table 7-39 relates conceptual and pedagogical issues. In Section 8.3.1 below, this is done by identifying potential starting strategies ('seeds') for a potential PCK agent to use in addressing the participants' various conceptual problems. These are not meant to be definitive, particularly as there is no such agent to use to determine their efficacy, but rather, they are an attempt to flesh out the *kinds* of things that a PCK

20. Based on the research conducted in this thesis.

21. i.e., as a general conclusion; this does not imply that these issues apply to all participants equally.

agent might reasonably be capable of doing. These may be significantly different from what an experienced science teacher might do in a classroom situation — even the 'best' software, after all, is not necessarily as responsive and adaptable as an experienced classroom teacher might be, nor is it necessarily able to facilitate (if at all) the same kinds of classroom structures and strategies that can be achieved in a (real) classroom.

In describing these PCK seeds, and relating them to the participants' subject matter knowledge difficulties, I have adopted the essential principle underpinning the Ontology Design Environment[22] (ODE) (Blázquez, Fernández, García-Pinar, & Gómez-Pérez, 1998; Gómez-Pérez, Fernández, & de Vicente, 1996) — a standard descriptive format that can be adapted to different programming languages[23] — that a particular event, such as in one of the planetary probes, can be ordered and described in a hierarchical record structure[24]. Blázquez et. al. (1998) suggest using such intermediate forms of representation in conjunction with translators such as MENTHOLOGY (Fernández, Gómez-Pérez, & Juristo, 1997) to create an ontological structure from tabular property lists (cf. Keil, 1989, p.25-30). This has the advantage of using tables as intermediate representations of the desired knowledge base in order to '...bridge the gap between how people think about a domain and the languages in which ontologies are formalized.' (Blázquez et al., 1998, p.1), which is why it is useful here[25].

22. i.e, the use of property tables with a specific structure as defined by the ODE — the ODE environment itself was not actually employed here.

23. a term inclusive of ontological and knowledge-building tools.

24. The alternative was to adopt a specific, structured, ontological programming, or knowledge specification, language such as *Ontolingua* (Farquhar, Fikes, & Rice, 1997; Gruber, 1993).

It is a relatively simple task to use the ODE format to describe the gravitational contexts (instances, class instances, and instance attributes) used in the interviews. For example (without fully completing all of the levels[26]), the planetary probes could be described as an instance[27] of the gravity ontology[28], with each particular type of probe (single planet, binary, multiple particles) each forming a particular class attribute of that instance, as below:

Data_Dictionary ->

Concept_Name:	Gravity
Synonyms (0..n):	Gravitational force, field, ...
Acronyms (0..n):	NIL
Instances (0..n):	**Planetary**, projectile, ...
Class Attributes (0..n):	Single, Dual, Multiple
Instance Attributes (0..n):	Mass, Velocity, Pos(r,ø), ... (0..n)
Relations (0..n):	N1, N2, N3, ...

While defining a particular class of event (such as BlueWorld[29]) in this way is relatively straight forward, producing a *complete* functional ontology requires a far richer and more complete set of super- and sub-ordinate classes than is the case here[30] (cf. Murray, 1996). However, even in the absence of a complete ontological structure, the notion of using property lists is still attractive as they combine simplicity with flexibility as to how, and what, to represent, and for this reason have been adopted for use in this chapter.

25. Most other tools of this kind require complex manipulation and formulation of the knowledge structures to accommodate their requirements, whereas with ODE, the articulation of property tables is much simpler, and more explicitly related to the knowledge and events that they attempt to depict.

26. for the purposes of this chapter, only aggregated class errors (i.e., for all participants) based on Table 7-38, will be described.

27. the actual instance attributes are more complex than listed here, and would identify the variables and contextual matters that comprise the actual instance (i.e., probe) — for example, as detailed in Section A.5

28. each 'concept' forms part of a complex ontology; gravity would only be one node in such a structure.

29. see Section 6.4.1.2 (c) on page 201.

30. i.e., the data here do not form a complete knowledge set for gravity, but are merely elements of it.

8.3.1 Conceptual difficulties

Participants' conceptual difficulties can be accommodated in the ODE framework as an additional field — 'Error attributes', as in Error (0..n), following the Class field[31] (cf. Figure 8-1). These error attributes could be inherited by a PCK agent (cf. the dotted lines in Figure 8-5), to initiate it's acquisition and development of appropriate pedagogical strategies in response to prompts from the knowledge management system (as in Figure 8-7), effectively telling the PCK agent that 'the user has problems with this - fix it!' This principle is used in Table 8-1[32] (below) to explore the conceptual-pedagogical relationship between the respective knowledge bases by relating particular conceptual problems to potential PCK seeds — in effect, concretising the data presented in Table 7-38 on page 351 and Figure 7-40 on page 352. Note that this is not a complete description in so far as Instance and Class attributes are not included because what is being examined here is the general relationship between the knowledge bases, not every instance of every class.

The types of PCK seeds suggested below are probably quite inadequate indicators of what might be achievable in a fully developed PCK-enhanced software environment in the future, given the massive increases in computing power, bandwidth, and storage capacity predicted over the next five years, when streaming video, multimedia, and virtual reality environments are expected to be both widely supported and freely deliverable over extensive broadband networks (Zemin, 2000). They are, however, realistic in terms of the current technologies employed in schools, and are intended to indicate how particular genres of current science

31. Because the error presumably relates to a particular CLASS of events.

32. Developed from Table 7-38.

education software may fit into the wider picture of Hestenes software curriculum. It is noteworthy that the software that can be used across a variety of tasks and problem types usually addresses higher-order cognitive processes. Even though the seeds presented in Table 8-1 (which is continued over several pages) appear to be straight forward, in fact they would rely heavily for their successful implementation on the existence of an (avatar) teacher being constructed around a comprehensive pedagogical knowledge base that embraces and delivers a realistic implementation of classroom teaching expertise (cf. Murray, 1996, p.235). Without this, these suggested tasks will likely 'degenerate' into a set of activities (as opposed to effective learning tasks) without significant cognitive impact on learners (cf. Hestenes' 'junk software').

Table 8-1: Gravity: potential PCK agent seeds for particular error attributes.

Subject matter knowledge agent 'Error attribute' (n)	**Potential PCK agent 'Error attribute' (n) seeds**
0. Newton's Laws (N1-N3)	
A. Can't describe or apply	Socratic dialogue labs with avatar tutor as per Hake (1992) with simulated laboratory work. Virtual reality experiences - (e.g., Dede et al., 1996) Exploration (e.g., Cockburn & Greenberg, 1995; CONDUIT, 1982)
I. Concept of gravity	
A. Can't explain	Cause and effect discussed by (avatar) tutor - multiple forms of evidence presented and analyzed (cf. Linn & Hsi, 2000).
B. No causal model	Empirical basis of N4 reviewed with tutor: video, multimedia. Relation between inertial & gravitational mass discussed with avatar (cf.Arons, 1990, p.58)

Table 8-1: Gravity: potential PCK agent seeds for particular error attributes.

II. Field concept	
A. No apparent field model	Simulation and modelling exercises of field/ force relationship. e.g., StarLogo (Resnick, 1997), (Alexandrov & Soprunov, 1997), (McCauley, 1984) Field plotting activities cf.Kirkup (1985; 1986). mathematical model and visualization (e.g., Chien, 1999; Dede et al., 1996)
B. Capture/influence zone	
C. Equipotential surfaces	
D. Force in field	
III. Action	
A. Local vs. Remote	Socratic dialog labs. to detail similarities & differences (e.g., Hake, 1992) Visualization-vector representation e.g., with Interactive Physics type environments (Knowledge Revolution, 1992) Mathematical argument from F=ma; graphs of a vs. M; videos of falling objects similar to Road Runner probes
B. From mass (cf. between)	
C. Mass dependent acceleration	
D. Action - reaction	
E. Buoyancy	
F. Different from force	
1. *Both act together*	Vector visualization to show forces acting - as in Vector probes and subsequent review by virtual tutor. Modelling force & vectors (e.g., McCauley, 1984; Trimble, 1986) Collaborative visualization of force concepts (e.g., Gomez et al., 1997)
2. *Unspecified action*	
G. Selective	
1. *Not in space*	Modelling force & vectors (e.g., McCauley, 1984; Trimble, 1986) Collaborative visualization of force concepts (e.g., Gomez et al., 1997) Socratic analysis of N4
2. *Created when needed*	
3. *Created at close range*	
4. *Speed*	
H. Pushes & Pulls	Socratic dialogue labs with avatar tutor Hake (1992)
IV. Presence	
A. No criteria for detecting	Socratic dialogue labs with avatar tutor Hake (1992)
V. Cause	
A. Earth's rotation	Interactive exploration (e.g, Fu-Kwun, 2000)

Table 8-1: Gravity: potential PCK agent seeds for particular error attributes.

B. Active force	
1. *Of Motion*	Adamson (1988), Back (1996)
2. *Of Object*	
3. *Speed dependent*	
VI. Representation	
A. Field	Immersive VR experiences (e.g., Dede et al., 1996)
B. Force	
1. *Concatenation & Superposition*	Interactive exploration (e.g, Fu-Kwun, 2000)
2. *Vectors*	Cognitive modelling (e.g., Trimble, 1986);
3. Frame	Use of visualization software to relate mathematical or physical representations (e.g., Chien, 1999; Fu-Kwun, 2000)
VII. Argument	
A. Non-Newtonian	Socratic dialogue (cf. [illegible]ke, 1992) with avatar tutor. Use of 'Newtonian' learning software (cf. Andaloro et al., 1997).
B. Inconsistent	Consistency tool (Section 8.3.3) shows student how & where they are being inconsistent
C. Can't contextualise	Experience in multiple contexts (e.g., Andaloro et al., 1995; Back, 1996; Hennessy et al., 1990; Selman, 1994; Sherin et al., 1993; Sokoloff, Thornton, & Laws, 1999)
D. Mathematical dependence	Use of visualization software (e.g., Chien, 1999)

Table 8-1 suggests that it is not only important to have a PCK agent that can offer and implement a wide range of pedagogical strategies, but also one that can implement them in a wide range of software architectures[33] e.g., virtual reality, simulation and modelling, visualization (in it's many forms), and avataristic simulations of human-human interaction, e.g., 'face-to-face' tutorial and Socratic dialogue. This must be a specific element of a PCK agent's design. Figure 8-8

33. i.e, those listed in Table 8-1are only a small sample of a wider range of software that could be used there.

shows how this could be implemented, conceptually, in the PCK agent by the inclusion of an environment manager, and dialogic manager to facilitate the inclusion of a wide range of 'didactic' models and software genres. In this conceptual model, the role of the dialogic manager would be to implement, in the avatars, particular kinds of dialogue (Socratic, 'didactic', etc.) within the particular environment being used. As such, it would be a 'linguistic engine' that would allow a wide range of discourse processes to be implemented in ways that could be used in a particular environment. i.e., the inclusion of this feature, while increasing the complexity of intra- and inter-agent processes, may provide the avatars with the ability to select a mode of discourse 'on the fly' as needed — as is commonly done in classroom teaching. The environment manager is the interface between the particular pedagogical model being employed, and it's mode of representation (avatar or 'software').

Figure 8-8: A possible software structure to support multiple software and discourse genres in PCK-enhanced software environments.

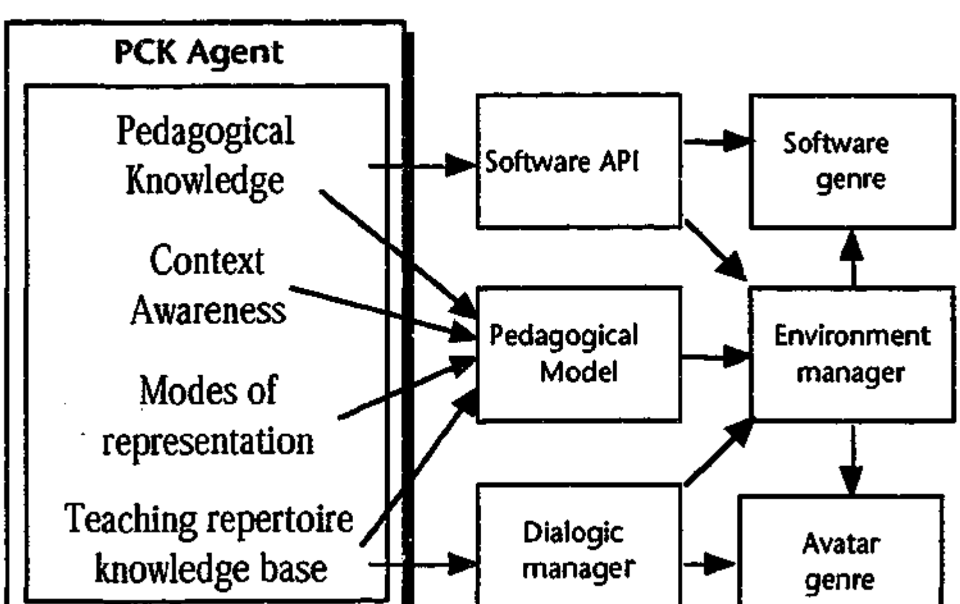
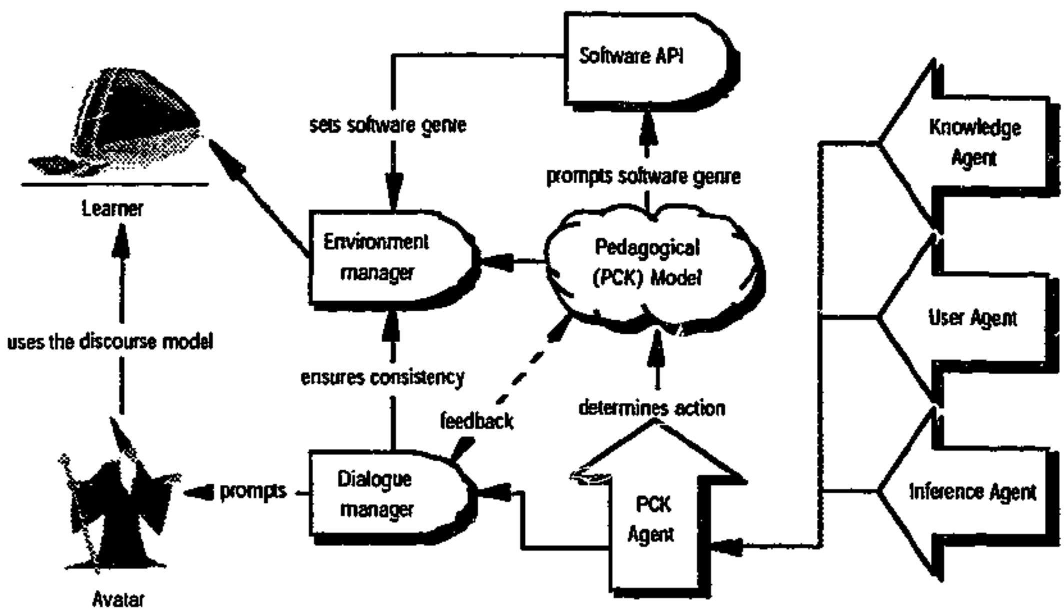


Figure 8-9 shows how these structural elements could be implemented in the case of the proposed PCK model (Figure 8-5). Figure 8-9 is intended to show the general flow of control (i.e., at a conceptual level only) that might allow for the implementation of context sensitive, dialogically driven avatars, and a range of software environments.

Figure 8-9: How the structural elements proposed in Figure 8-8 could be implemented.



8.3.2 Problems with representation

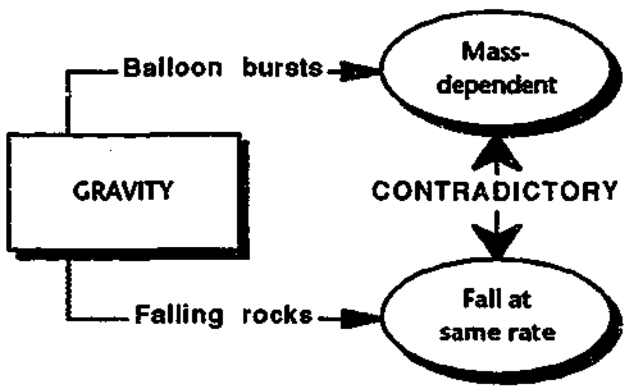
Many of the participants had great difficulty in making effective use of correct or appropriate representational forms during their interview, suggesting a need to explicitly address this by ensuring that they are exposed to, and aware of, a range of appropriate representations of concepts at any instance or class. At a basic level, this appears to be a simple task, with the PCK agent simply presenting a different representation each time a user engages with a specific concept. However, this is probably a naive approach as the impact on the user is not at all clear, and may, or may not, confound their understandings of the concept being examined. For example, if Jim (Section 7.2.5 on page 281) were to be presented with a different representation of accelerated motion (cf. Figure 7-19) each time he explored projectile motion, would that significantly impact on his problems with invalid vector addition methods? There is presumably a complex relationship between content knowledge and use of representations that needs to be articulated. For example, it *may be* a better approach to relate the frequency of use of different representational forms to some measure of the user's success with understanding the concept being presented, but (again) there is no data to determine which would be best, and why. Any such process could be prompted by the content agent alerting the PCK agent (as in Figure 8-5), or through the adaptive nature of the PCK agent. This issue of representational selection is likely to be a very important aspect of PCK-enhanced software, and presumably requires considerable theoretical consideration of alternative models of implementation.

8.3.3 Problems with inconsistency

Lawler's microview model, which forms the cognitive conceptual framework for considering PCK in this thesis (as described in Section 3.1.1 on page 57), is useful in considering the implications of the participants' common use of 'inconsistent' or 'contradictory' responses, in which concepts or laws were posited in one context, and then often negated or restructured in another. Being cognisant of Keil's caution (1989, p.282) that, '...the attribution of a particular theory to an individual may prove more troublesome than it appears at first', it should be noted that the following is presented as an example of how Lawler's model *can* be used to explain the use of inconsistent argument, and not to imply that Joe's cognitive state has *actually* been gleaned from the data, i.e., that speculations about the nature of his P-prims and microviews in this example are simply that — speculation.

Joe explains that, when talking about a balloon bursting, objects fall at a rate that *depends on their weight* (1:88), but subsequently, when discussing falling rocks, states that falling objects would all fall *at the same rate* (1:103). This usage of multiple explanations can be represented, in Lawler's model, as two different methods that are contextually cued (Figure 8-10).

Figure 8-10: Simplified microview depiction - use of two methods in explaining gravity.



In Lawler's model, this can be understood as Joe, perhaps, having a P-prim for falling (i.e., in the case of the rocks), and a P-prim for floatation (i.e., in the case of the balloon). Observing each event (the rocks falling or the balloon bursting) causes his (presumed) internal P-prims to cue the specific, contextual, recognition of an instance of a category (falling or floating), which then presumably activates a task-rooted, contextually-bound microview to generate the appropriate response — nence two apparently contradictory responses that appear, to an external observer, to be inconsistent. Joe, however, is presumably not aware of any inconsistency, since he has not developed higher-level P-prims[34] (cf. diSessa, 1993b, p.114) or

34. Lawler describes P-prims as microviews *without* methods (R. W. Lawler, personal communication, 13/08/1994).

conformal or coordinating microviews that integrate these into a coherent cognitive schema (cf. Figure 3-7 on page 59). Joe's (presumed) falling 'microview' is aligned with Newtonian mechanics, but his (presumed) one for floatation is not, yet Joe seems unaware of any inconsistency. An implication of the use of such inconsistent argument is that, as is implicit in Lawler's model, Joe's knowledge is effectively highly contextualised, situated in specific phenomenological events, and compartmentalised; there is little, if any, holistic understanding of the various events that trigger P-prims. In more familiar conceptual development terms, Joe's knowledge has not acquired a theoretical structure or 'generalisation' or 'specialisation' (e.g., Chinn & Brewer, 1998, p.99; Glaser, 1991, p.403) that leads to his responses being generated by higher-level constructs (cf. Lawler's conformal microviews and diSessa's higher order P-prims[35]).

What has been argued above, using Joe as an example, is that one key aspect of the participants' problems with gravity is due to their knowledge of specific context, situations, or laws, being *compartmentalised and highly contextualised*[36]. A similar argument could be mounted for other participants in this thesis, using the examples in Table 7-39 on page 356. On this basis, there is a need for explicit 'remediation' of such inconsistent arguments to be embedded in the PCK and knowledge management agents. The essential functionality of such a tool might be along the lines of that described below in psuedocode[37], where response(x,y) is the current response to class(y) of instance(x), response(i,j) is a previous response, and the

35. for example, 'springiness' (diSessa, 1993b, p.141).

36. This is, arguably, indicative of the shallow learning of concepts (Brown, 1988), which may, or may not, be related to a shallow approach to learning by the participants (e.g., Ramsden, 1988, p.19).

37. Instance and Class Attributes refer to the ODE model categories.

operator 'consistent' evaluates their consistency:

Program 8-1: Possible basic functionality of a tool for addressing inconsistent conceptual understandings in an PCK-enhanced, agent-based system.

```
For each Instance (0..i)
    For each Class Attribute (0..j)
      If not consistent Response(x,y), Response (i,j)
          Output Error (x,y,i,j)
          Output Alert_PCK(x,y,i,j)
```

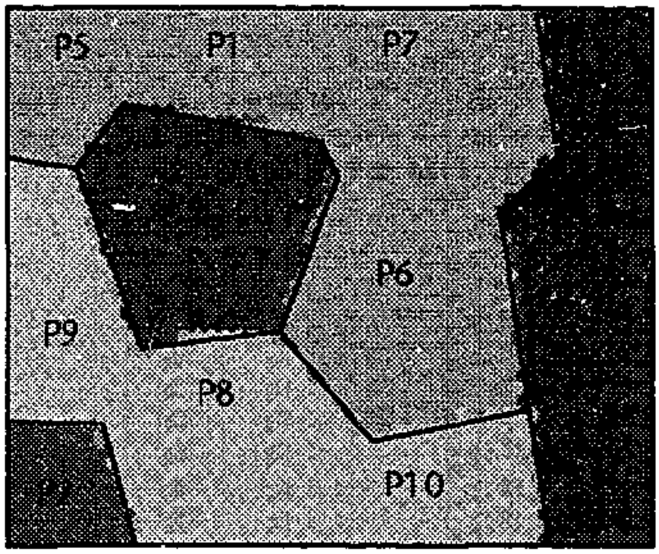
When the current response is inconsistent with a previous response to any other instance of the concept, this tool informs both the PCK and knowledge management agents of the instance and class, so that they can initiate their particular remediation strategies as described in Section 8.2.3.

8.3.4 Supporting group processes: teaching a class

Figure 8-11 is a graphic representation of the participants' misconceptions about gravity (generated as a self-organizing map)[38] which shows how the participants appear to cluster[39] (i.e., have strong similarities[40]) in their FCI-deduced misconceptions about (in this example) gravity[41].

38. Honkela (2000).
39. based on the FCI scores, a statistic generates a two-dimensional representation of differences in responses.
40. this is somewhat arbitrary, as the exact nature of the representation depends both on the variables used to create the map, and internal parameters in the program.
41. FCI data are presented here as software limitations prevented a comprehensive mapping of the interview data.

Figure 8-11: Self-organising map representation of participants' difficulties with gravity (as deduced from the FCI). (boundary lines added)



A pedagogical agent might well be able to use the type of data presented in Figure 8-11 to select appropriate pedagogical strategies for particular *groups* (i.e., focusing on minimising inter-group differences, or maximising intra-group interaction) as well as simultaneously aiming to improve each individual's subject matter knowledge; suggesting a potential software approach to 'teaching a class' and also providing individual, customised, 'tuition'. It might be argued that this is inconsistent with the purposes of the intelligent tutoring system being used as an example here — with it's explicit focus on individuals. However, in contexts such as those proposed by Hestenes, it is quite likely that human social processes (such as communication, interaction, exploration) will continue to be an essential, valuable, component of Education, and will need to be supported in software environments.

Pedagogical agents like Adele, that explicitly support multiple users, are potentially able to accommodate a PCK-agent that might include 'class management' strategies that embrace pedagogical structures to facilitate productive discourse between users; this implies much more than the use of electronic conferences — rather something akin to the ways in which teachers employ a variety of classroom organisational structures (small-large groups, presentations, etc.) to support a variety of learning outcomes and social interactions.

It may therefore be pedagogically beneficial to allow a focus on groups of learners with similar kinds of conceptual difficulties so that some intra-group activities can be developed (such as a jig-saw model, or class discussion of an issue), rather than the technology fragmenting classroom structure to create a set of autonomous, individual, presumably 'disconnected', students working largely on computers — a vision reminiscent of Papert's cautions about technocentric thinking (Papert, 1987).

8.4 Speculations about developing expertise

This section speculates about how the development of expertise[42] might be facilitated[43] by PCK-enhanced software — for example, in helping Joanna[44] develop both a better understanding of the NFC (e.g., as measured by an improvement in her poor FCI score), and her ability to readily and easily apply it across a range of new or unfamiliar contexts (as opposed to her current difficulties with common physics contexts and concepts). It is important to note that this is (arguably) different from the development of the kinds of cognitive competencies that many intelligent tutoring systems (ITS) are based on. For example, if we posit a case where Joanna's difficulties with explaining Homer's leap (Section 7.2.1.3 (a)

42. e.g., developing deep, incisive understandings of the ontology and cognitive basis of, say, the NFC as depicted in Figure 4-8 on page 105.

43. while noting Murray's (1996, p.235) comment on the difficulty of capturing and describing it.

44. See "Joanna" on page 246.

on page 251) are being addressed by means of, say, exploring a number of cases of projectile motion (using a variety of representational forms as discussed in (Section 8.2.3), then most ITS will 'simply'[45] aim to minimise the differences[46] in her responses from the 'expected' response in an iterative manner. However, while this might ensure that she can produce the 'correct' response, it does not guarantee that she has developed 'expertise' with the relevant concept or law — as the majority of the data presented in Chapter 7 indicate in the case of the FCI (i.e., better understanding of the FCI does not ensure expertise in applying it to the gravitational contexts examined in Chapter 7).

I argue that this is because the competency models that underpins most ITS are structured around achievable competency statements (i.e., with a structure similar to 'behavioural objectives'), rather than on the development of higher order thinking. This is presumably because of the difficulty in defining and articulating specific instances of such thinking that can be 'captured' (Murray, 1996, p.235) and subsequently used to evaluate learners' responses (as above). There is, prima facie, a need to implement some explicit cognitive scaffolding or pedagogical processes to maximise the potential for the development of higher order thinking — e.g., that Joanna will acquire the *expertise* needed to be able to interpret and correctly explain a wide range of NFC-related contexts through the acquisition and use of higher order thinking skills that are qualitatively different from, in Bloom's (1956) terms, recall or application (cf. Herrington & Oliver, 1999).

45. as explored in this chapter, the underlying mechanisms whereby this occurs are complex.

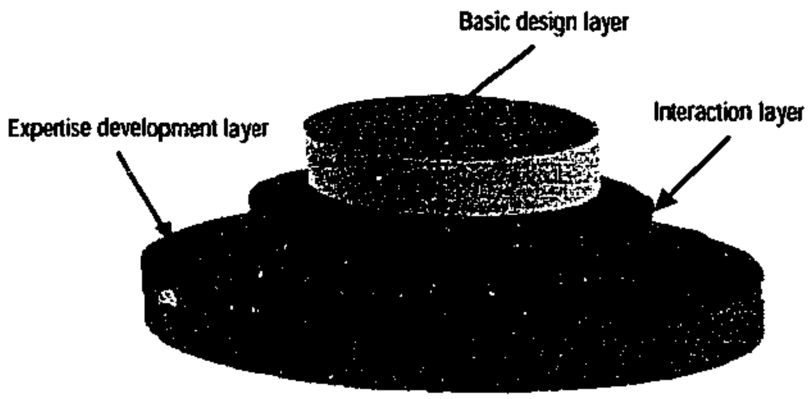
46. as evaluated by the knowledge management agent in, for the purposes of this argument, an undefined manner.

If, in fact, the essence of expertise is so difficult to define and implement in an ITS as to make it's incorporation unlikely, then there is a need to consider alternative approaches to it's development — such as in the nature of the interactions between the users of such software, i.e., in the social construction of knowledge between and amongst learners, rather than in the 'delivered wisdom' of an ITS; after all, Hestenes (Section 1.1) was arguing for technology to reform, not to supplant, science teaching. Therefore it *is* important to 'step back' from the focus on PCK-enhanced software per se, and to consider it's use in a community of learners, where social processes are an important component of knowledge development (e.g., Bandura, 1996; Berger & Luckmann, 1967; Brown et al., 1993; Cockburn & Greenberg, 1995; Osberg, 1997; Salomon, 1993).

A tentative model for developing higher order thinking (Nicholson & White, 2000a; 2000b) is described below in the form of a simple layered-design model that facilitates scaffolded social interaction, and also facilitates instructional design to support it's implementation. This model originated in the research on learning environment design conducted for this thesis[47] (e.g., Nicholson, 1999; Nicholson & White, 2000a; 2000b; 2000c), and in related work (also originating in this thesis) on the development of metacognitive learning environments (e.g, Nicholson, 1995, 1998; Nicholson & Johnson, 1998) and in the development of a distributed-multimedia professional development project (Kruze, 2000).

47. what is reported here is the work of the author of this thesis: in dual authored papers, the role of the second author relates to either adult learning and workplace contexts (White), or to the *use* of the actual environment (Johnson).

Figure 8-12: A layered-design model for developing higher order thinking.(Nicholson & White, 2000b, p.9)



The purpose of this model is to provide a simple design model that focuses attention on the development of expertise, rather than the acquisition of subject matter knowledge. In the context of the PCK-enhanced software environments explored in this chapter, Figure 8-12 presents a different logical view of Figure 8-9, with the 'basic design layer' essentially relating to all of the entities, except the pedagogical model. The interaction and expertise development layers in Figure 8-12 relate, respectively, to processes for ensuring that learners are actively engaged in the environment, and that appropriate social processes for developing expertise are incorporated into such active engagement (i.e., that such engagement is not simply a technocentric behaviourist interaction). If the interaction and expertise layers were mapped onto Figure 8-9, they would fit into the 'pedagogical model' component where their role would be to ensure that suitable pedagogical, dialogical (i.e., via the avatar), and software models were implemented so that the development of higher order thinking was facilitated — possibly the most complex of all tasks required of the PCK agent.

The model differentiates between interaction and the development of expertise, as the two are fundamentally distinct, a point often overlooked in traditional learning contexts. Simply planning structures and processes such as learning sequences, discussions and on-line seminars etc. (i.e., the task of the PCK agent and knowledge management agents) to engage learners with content is insufficient for the facilitation of higher order learning. These components must be supplemented by the purposeful development of expertise arising from such interactions. The model's particular structure stems from the recognition that most traditional instructional design paradigms are unable to cope with the nature, scope, and incorporation of uncertainty and values that fuzzy[48] contexts, such as the development of expertise, contain (which was essentially Murray's argument in the opening quote to this chapter). As a general proposition, I argue that any instructional design model that purports to address fuzzy contexts (such as the development of expertise) must include aspects that deal with, at least, the following as basic design requirements (Nicholson & White, 2000a; 2000b):

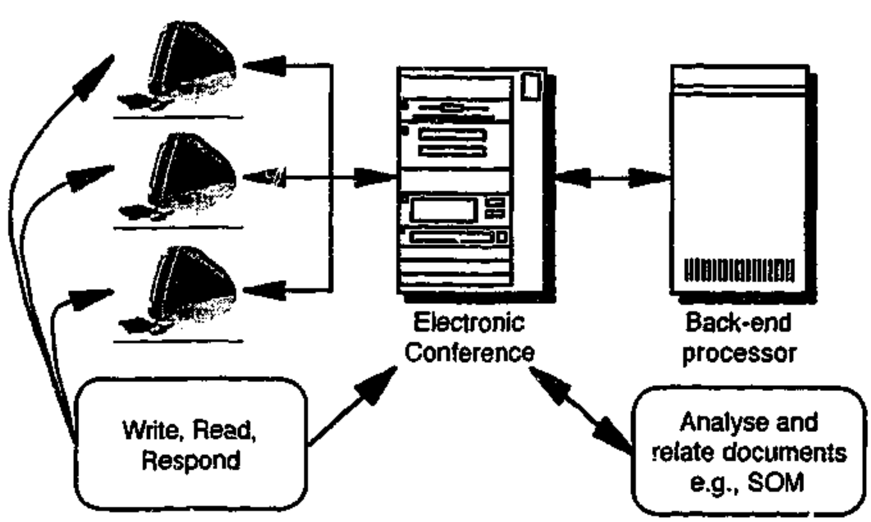
1. Uncertainty ('fuzziness') — an expert practitioner should be able to cope with 'real world' problems and experiences as well as with the formal contexts of the relevant discipline or domain.
2. Decisions on a path of action — expert practitioners should be able to apply their expertise to determining the best course of action in a particular circumstance.
3. Judgement & interpretation — hallmarks of expertise.
4. Multiple perspectives — understanding alternative perspectives (e.g., those in Section 4.2), and being able to relate to them is central to the notion of possessing an expert understanding of a field.

In order to accommodate these features, I argue that the traditional instructional design process of creating a predetermined learning sequence (and perhaps even those that might result from the adaptive PCK-agent discussed in this chapter), needs to be modified to be with one that creates a set of loosely structured learning

48. i.e., in the A.I. sense of having a non-deterministic solution.

pathways (cf. Nicholson & White, 2000b, p.9), and provides opportunities for reflective practices (e.g., Nicholson, 1994b, 1995, 1998; Nicholson & Johnson, 1999) and social interactions. The following example, based on this principle, attempts to concretise this notion of explicitly planning for expertise development. There is, however, much work to be done on identifying the range and functionality of other methods of implementation that might be useful in a similar role. The model below (Figure 8-13) should not be seen as definitive, but rather as one example of how the layered-design model might be implemented with a multi-user agent like Adele.

Figure 8-13: Simple example of a structure for developing expertise



For the purposes of this example, expertise is assumed to grow as a result of a number of interrelated cognitive processes — artefact construction (Schroder et al., 1996; Spitulnik, Stratford, Krajcik, & Soloway, 1998), metacognition (Borkowski, 1992; Fortunato & Hecht, 1991; Johnson, 1995), reflective practice (Baird, 1987; Baird & Northfield, 1992), and analysis and critique (of, and from, other learners) (cf. Nicholson, 1999; Nicholson & Johnson, 1998). This model stems from both

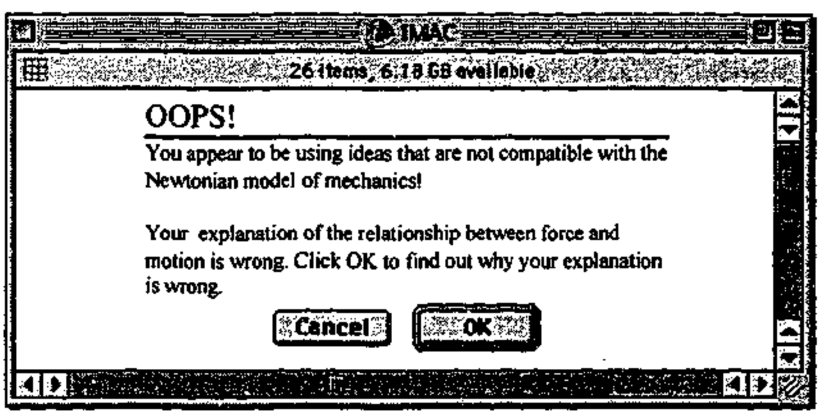
Ludwig Wittgenstein's belief that is only the attempt to write down your ideas that enables them to develop (Drury, 1982), and work by Pea and Kurland (1987), Brown (1985), and Collins and Gentner (1980), on the role of technology in supporting purposeful writing.

In this model, a clearly defined role for the use of technology in supporting writing is essential. For example, in 1987, Pea and Kurland (1987) reviewed the then currently available technologies for writing, finding that they offered neither qualitative advances over previous tools for mature writers, nor benefits for novices. Noting that writing had many constraints that dictated its form (e.g., Collins & Gentner, 1980), they recommended the development of 'cognitive technologies for writing' that would produce better writing by linking 'thinking' with 'writing', and which would have a different order of magnitude of effect over the use of routine spelling and grammar checking programs. These were to be 'idea amplifiers' (Brown, 1985), something that would help a writer to develop the cognitive skills necessary for writing in order to facilitate better writing. Technology was not seen as a barrier to development—'most of the remaining barriers to creating such writing environments are conceptual...' (Pea & Kurland, 1987, p. 278). While not foreseeing the Internet, their vision accommodates it, and its existence facilitates their development. These are the conceptual origins of the expertise model in Figure 8-13.

In practice, groups of users, perhaps selected as discussed in Section 8.3.4, would work on a particular topic, such as Newtonian mechanics, and in addition to engaging in the 'routine', PCK-aware tasks generated by the ITS (Figure 8-9)[49], would be required to write about their understandings (in an electronic conference), and to read, and to critique, other learners' writings (perhaps a task better suited to adults than children). This alone does not significantly implement the kinds of ideas developed by Pea and Kurland, Brown, and by Collins and Gentner — it does not, for example, explain how the use of technology in this model forms an idea amplifier to support higher order thinking; this requires further strategies, as discussed below.

The role of the 'back end processor' in Figure 8-13 is to analyse learners' writing according to whatever is being examined[50]. As a simple example, consider a case where a learner may be describing motion in an apparent Aristotelian sense[51]. Rather than explicitly 'remediate' the problem, as in Figure 8-14,

Figure 8-14: Sample error alert.



the system could use a self-organising map algorithm to produce a graphic depiction of where their ideas fit into those of the whole cohort (or any other group) (cf. Figure 8-11), and ask the learner to read, and respond to, 'more Newtonian' users, or suggest another learner with whom to have a dialogue over the issue, or even

49. which are, for the purposes of this argument, assumed to be sufficiently engaging as to comprise an effective implementation of the engagement layer

50. i.e., the model assumes the existence of appropriate algorithms to do this - something probably in need of significant theoretical development.

51. i.e., that presumably has neither been detected nor addressed by the knowledge management system.

bring up an avatar of Newton to discuss the issue with. The point being made here is that the learner is not provided with the explicit nature of their error and the orthodox means of remediation. Rather, they are being led along a path of reflective engagement with artefacts (and people) with the intention of acquiring the correct understandings. However, this also requires that their consequent writings are also reviewed and critiqued so that their cognitive movement is in the desired direction. With this process supported by technologies such as agents, self organising maps, and electronic communications, it provides some insight into Pea and Kurlands' notions of what cognitive technologies for writing might be like.

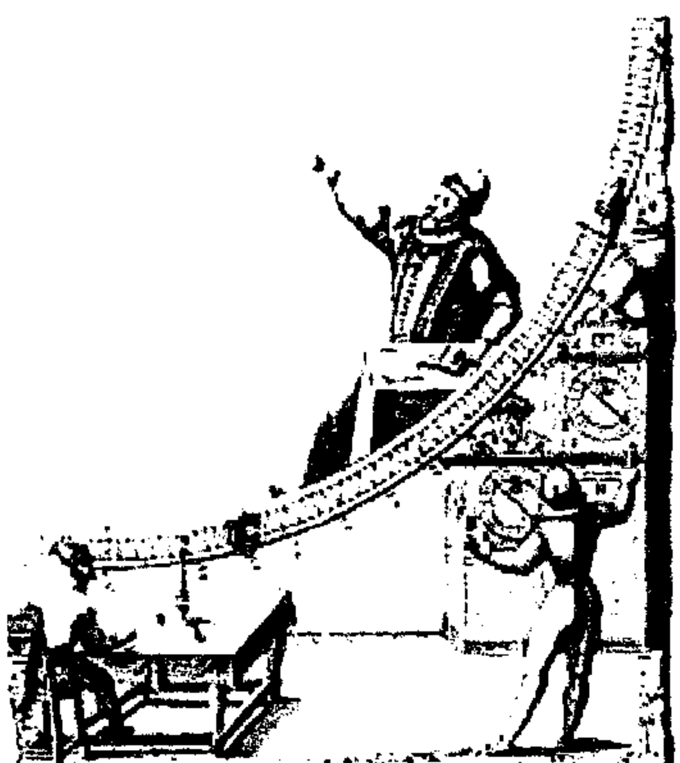
It's important to state that processes such as those briefly outlined above do not guarantee the development of higher order thinking or expertise. Rather, they attempt to provide conditions in which it is supported and hopefully facilitated by the learning environment. This is the point of having a model that explicitly includes expertise as a major feature — it requires significant thought about how this can be achieved, and on what basis, as the example above has attempted to show. In terms of this model (Figure 8-12), the challenge for science educators is to develop and describe learning models for supporting higher order thinking that can implemented in ways similar to those described here.

8.5 Chapter Review

In this chapter, the general nature of PCK-enhanced software was examined, and the method of implementation of a possible PCK-agent was identified as a key component of such software. The nature of key features (agency and knowledge acquisition) were examined. It was recommended that a PCK-agent should be implemented independently of any knowledge management system, with a functionality closely aligned to that of a (human) teacher. Examples of how this could work, using examples from the data, were presented. Particular pedagogical issues that were suggested by the data were discussed (representation, inconsistency, and resolution). The participants' aggregated conceptual difficulties were described in ways which would be useful for their accommodation in a knowledge management system. The chapter concluded with speculations on a possible model for developing expertise through the use of PCK-enhanced software.

Chapter 9

Conclusions & recommendations



9

Conclusions & recommendations

> The fatal pedagogical error is to throw answers, like stones, at the heads of those who have not yet asked the questions.
>
> Paul Tillich (source unknown)

9.1 Introduction

The research questions have been addressed explicitly in Chapter 7 (Section 7.3 - Section 7.5) and in Chapter 8. In Chapter 7 it was shown that the participants' problems with teaching the VCE unit 4 gravity curriculum were due to fundamental conceptual difficulties with the Newtonian concepts of Force and Gravity, which resulted in them having major difficulties in attempting to explain them (i.e., in the interviews). No evidence of emerging T-PCK was found in the data. In Chapter 8, possible attributes of PCK-enhanced software were examined in light of the data described in Chapter 7, and from contemporary software development paradigms. The nature and basic function of a possible PCK pedagogical agent was identified and described in functional terms.

In this chapter, I discuss issues arising from Chapter 7 and Chapter 8, as well as from the overall research process, and consider the implications of the work in terms of Hestenes' software curriculum to reform and revitalise science education.

9.2 A knowledge base for the VCE context

This section completes the work undertaken in Chapters 7 and 8 on identifying subject matter difficulties, and on determining the attributes of PCK-enhanced software, by describing a pedagogical knowledge base for the VCE unit 4 gravity context that relates the work conducted in those two chapters to the specifics of the VCE context — in effect, to validate those findings about ways to '...support and facilitate the development of both T-PCK and content knowledge in this area of the VCE curriculum' (research question 2 on page 43), by relating them explicitly to the actual classroom context in which they originated. In the short term, this may be directly usable in addressing some of the concerns with my physics-method students as expressed in Chapter 2, and therefore has a direct influence on my work, and immediately renders this thesis valuable for my teaching and my prospective students' learning.

The essentials of this knowledge base have already been described in Table 8-1 in terms of PCK 'seeds', which, while presented in terms of approaches applicable to PCK-enhanced software, are also directly applicable to classroom teaching[1] — particularly the normal classroom use of the software types listed there. Additionally, many have closely related, traditional, 'hands on' activities of a similar nature. For example, in the context of 'Field concepts' (Table 8-1), each PCK seed for use in the hypothetical PCK-enhanced software environment has a close classroom equivalent as in Table 9-1, demonstrating that those (at least) can be mapped on to 'normal' teaching processes. In addition, the items in Table 8-1

1. noting that the selection of software examples was dictated by the context of PCK-enhanced software.

could be used as a basis for 'simply' adding some basic pedagogical considerations to, say, ITS (e.g., Murray, 1990) or other physics content knowledge software (e.g., Dede, Salzman, & Bowen Loftin, 1996), while noting Hestenes' (1995, p.4) caution about the use of stand-alone software.

Table 9-1: Examples of classroom activities related to software PCK seeds.

PCK seed (software)	Classroom activity
Simulation and modelling exercises of field/force relationship.	Radial diffusion of phenolphthalein through gelatine; plasticine curved 'field mountain'.
Field plotting activities.	Plotting magnetic fields with iron filings in hot wax (or using a compass); sawdust on a van de Graaf generator; conductivity paper mapping.
Mathematical modelling and visualization	Graphing linear air track data for different instances of force and mass; strobe photography.

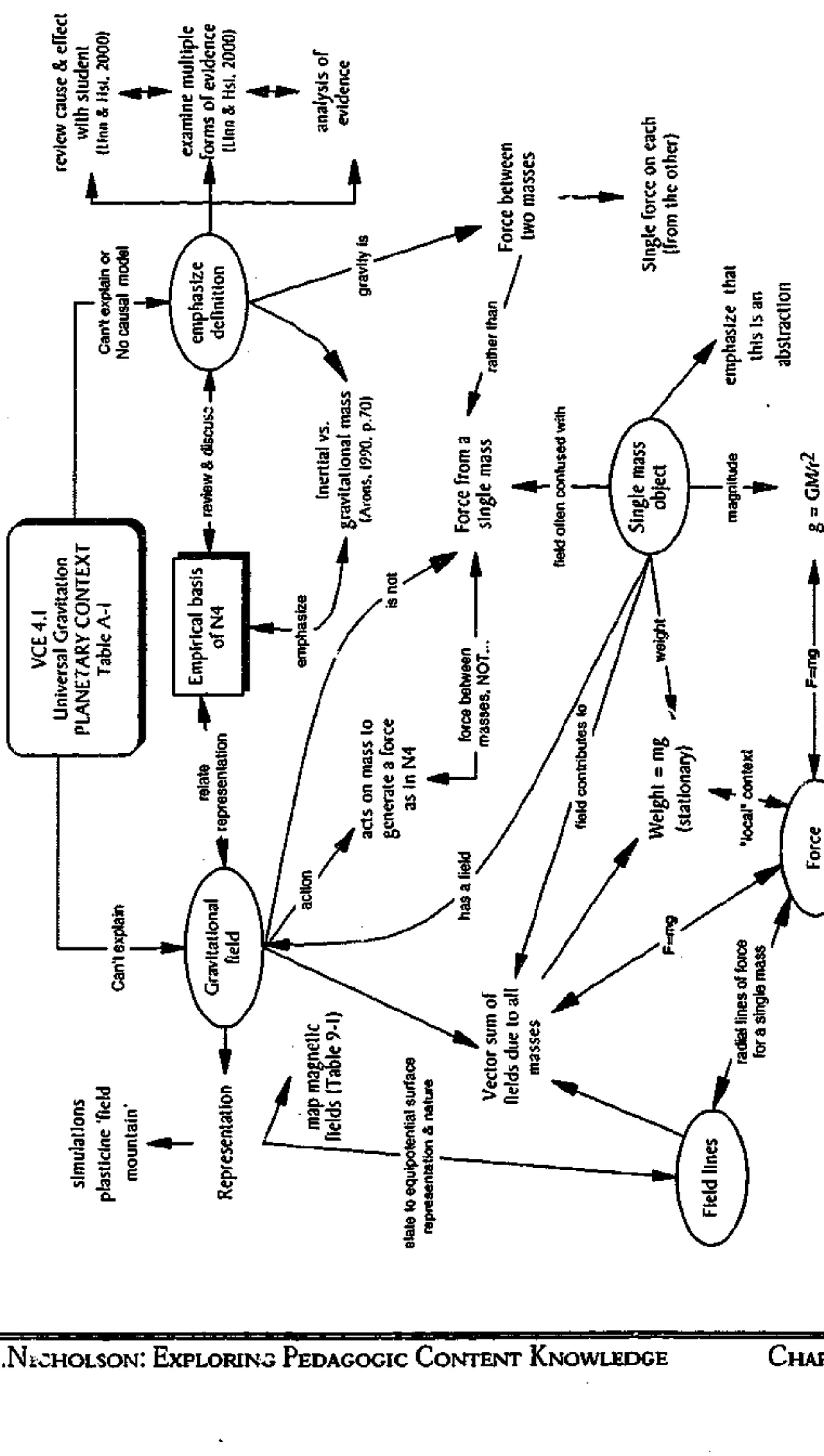
Note that in the following, the notion of a 'single mass' being introduced into a field, and subsequently experiencing a gravitational force, is a simplification, both pedagogical and mathematical, to simply the discussion about fields and force, and to remove the need to introduce perturbation theory into the mathematics. It also has significant potential to cause misconceptions about N4 and fields (because it is misleading), but like the example in Figure 3-6 on page 57, is an appropriate one for the presumed developmental level of the students to whom it is presented. In accordance with representations in Chapters 4 and 7, Figure 9-1 presents the mapping onto the VCE contexts in a graphical format. Figure 9-1 is an attempt to concretise the pedagogical issues that might help to address the conceptual problems identified in Chapter 7 (and which might, therefore, need to implemented in a PCK-enhanced software environment). As such it is intended to be indicative, rather than definitive, covering the major issues listed in Table 8-1, and identifying some key foci for teaching about N4 — it's empirical basis, that gravity is a force between two masses (cf. Arons, 1990, p.70), and the representation of fields and equipotential surfaces. These were common sources of difficulty for the participants (as described in Chapter 7).

While the content of Figure 9-1 appears simple and obvious to a Newtonian reader, as the data in Chapter 7 show, the content it refers to is clearly not simple to many learners, even those completing a science degree. In order to develop the items in Figure 9-1 in a classroom context, there are significant conceptual underpinnings required (as below) — both prior to, and during, developing it in a classroom context. Significant aspects of these are listed below, and continue *after* Figure 9-1. In particular, there is the need for a rich dialogue with student teachers about cognitive *and* pedagogical issues and their relationship (as identified in Chapter 7) such as:

- The mathematized abstractions that form the basis of N1 - N3 (cf. Koyré, 1968, 1978; Hake, 1992).
- The empirical basis of N4, and the relationship between inertial and gravitational mass, and implications arising from it — particularly that gravity is ubiquitous, non-selective in it's action, e.g., that it does not have 'capture zones' or 'zones of influence', is not mass or speed dependent — there maybe a need to relate these to rapid change of gravitational force with distance as in $1/r^2$, and the insightful and incisive drawing of free-body diagrams to determine 'what is actually acting on what'. There is also a need to address such obvious

aspects as how to detect it's presence (cf. N1/N2), and that N4 is consistent with N1-N3, which determine how gravity (*as a force*) acts on matter (i.e, the mechanics of motion).

Figure 9-1: Basic pedagogical considerations for teaching N4 and gravity.



- Discriminating between 'local' (i.e., a person on the surface of a planet), and 'planetary' contexts (i.e., as in the gravitational probes in Section 6.4.4), so that students can determine an appropriate contextual frame of reference, and select the relevant equations to employ in interpreting and solving problems (e.g., as with James, as in Figure 7-22).
- The nature of, and relationships between, quantities (cf. Jim's addition of Force and Momentum in Figure 7-15) and their *explicit* representation in vector (e.g., emphasising concatenation and superposition processes and representations) and field diagrams (e.g., comparing equipotential surfaces and 'lines of force').
- An emphasis on understanding contexts and situations in which each of Newton's laws, and Kepler's laws, can be applied to understand and describe particular mechanical, gravitational, and orbital, events.
- Cause and effect — helping students to avoid problems such as in Figure 7-16, where force and gravity were seen as two separate entities that acted together in some undefined way — and particularly in their use of N3.
- Discussion of common misconceptions — their nature, how and why they are wrong, and why people may hold them — including developing students' knowledge of explicit diagnostic processes to identify them (e.g., use of the FCI).
- Argumentative discourse processes (e.g., Hake's (1992) Socratic Dialogue Labs) to help to resolve misunderstandings at both cognitive and semantic levels, and to develop students awareness of non-Newtonian arguments, their rebuttal, and appropriate pedagogical approaches to address them.

The development and attainment of the correct understanding of all of the items above, including those represented in Figure 9-1, and an ability to apply them, is obviously a utopian outcome. However, by attempting to focus on the concurrent development of subject matter knowledge, and PCK (e.g., as in Figure 9-1), and by providing student teachers with a rich immersion in a variety of contexts (including those listed in Table 8-1), it can be hoped that more robust and accurate understandings of Newtonian mechanics and gravity, can be developed, that will hopefully (but not definitely) help to address Dykstra Jr's[2] (2000) and diSessa's[3] (1993b, p.1) concerns about learners' understandings of science, and their ability to apply that knowledge both qualitatively and quantitatively. In particular, it might result in responses to questions such as Suzie's (Section 2.1.1) being addressed from a more informed diagnostic and pedagogical stance.

9.3 Implications for teacher education

The apparent lack of subject matter knowledge in the participants of this study is a serious matter that needs to be addressed urgently (cf. Section 7.5). While it is possible that the participants' diverse backgrounds and curriculum specialisation (Table 2-2) may have contributed to their problems in some undetermined manner, this does not explain why the vast majority have significant problems with the area, and hold a number of common misconceptions about force and gravity, nor why the impact of decades of misconceptions research has apparently not impacted on practice (cf. Section 7.5.1).

Expert physics teachers, those with strong Newtonian understandings and the ability to embrace all of the issues and recommendations made in Section 9.2, should be able to both diagnose, and attempt to remediate, common misconceptions. I conjecture, however, that it is precisely because of a lack of such expertise in teachers generally (e.g., in the case of the participants of this thesis),

2. See Chapter 1, page 10.
3. See Chapter 2, p.age 15.

that misconceptions continue to flourish and remain effectively unaddressed. By drawing on the data in Chapter 7, it is apparent that Teacher Education contributes to this (to varying degrees) by sustaining a 'cycle of ignorance' in which those deemed competent to teach (physics) are in fact not; having apparently gained neither adequate subject matter knowledge, nor appropriate PCK to use in addressing students' difficulties with Physics during their undergraduate years.

In the case of the participants of this study, I conjecture that a significant element of their problems arise from structural features in the BES (Section 2.6.1) where there was little, if any, *explicit* integration of the teaching and development of subject matter knowledge and PCK between the two responsible faculties— an 'integrative' model (Gess-Newsome, 1999, p.13), and the Practicum component of the participants' course. The serious level of misunderstanding of basic Newtonian concepts identified in Chapter 7 suggests that there is an urgent need to find ways to develop holistic, perhaps situative, understandings of Newtonian mechanics, and ways and means of teaching it effectively to students. While PCK-enhanced software, and Hestenes' software-curriculum may provide longer term solutions, there is clearly a need for a more immediate solution — one that better integrates subject matter knowledge, PCK, and the participants' teaching experiences during their practicum, and one that can be realistically implemented in the context of the current program[4].

Feinman-Nemser (2001) notes that mentoring is an area of growing interest in teacher education (cf. Section 8.2.1), and that assigning experienced teachers to

4. Which is not able to be extensively modified in the short term.

work with beginning teachers might be a useful strategy to support beginning teachers. However, 'Still, we know relatively little about what thoughtful mentor teachers do, how they think about their work, and what novices learn from their interactions with them.' (Feinman-Nemser, 2001, p.17) In the case of the participants of this thesis, the issues and approaches developed in the previous section (Section 9.2) provide a framework for scaffolding their practicum experiences, acting as a framework to guide their teaching activities and their observations and discussions with their supervisors. What is particularly useful about this notion, is that it can potentially refocus their practicum onto pedagogical issues beyond the pragmatics of classroom operations, tying together (as in Shulman's model of PCK), both subject matter knowledge and the 'craft knowledge' of teaching. Such an approach would also cause a potentially significant refocusing of the supervisor's role from that of an 'assessor' to that of a mentor, which may lead to more effective knowledge and skills transfer to the participants than (apparently) occurs at present. For example, the data in Chapter 7 do not suggest that the participants have actually acquired a deep, or even basic, classroom (craft) knowledge and understanding of the relevant concepts, let alone how to teach them.

I suggest, therefore, that practicum experiences based around specific science content areas — such as Physics, Chemistry, etc., should be developed with the explicit inclusion of PCK and subject matter knowledge considerations such as those described above; that preservice teachers and their supervisors have some formal understanding of mentoring processes and expectations, and that the acquisition of PCK related to subject matter knowledge (i.e., other than classroom management, curriculum knowledge etc.), should be an explicit and clearly articulated focus of the practicum experience. In this way, it is hoped that the practicum will become an integrative element of the student teachers' course[5], and lead to '...educative experiences, which are experiences that promote, rather than retard future growth and lead to richer subsequent experiences' (Feinman-Nemser, 2001, p.52). Hopefully, at some future time, software such as the PCK-enhanced model described in this thesis, will assist in this process.

9.4 Methodological issues

This section addresses several issues arising from the chosen research design, and the instruments employed in its conduct.

9.4.1 Clinical versus classroom research contexts

In Section 5.5.1 on page 154, I addressed methodological questions raised by Niedderer et.al. (1992, p.11), and by Lemke (1998, p.1185), about how the differences between educational research performed in clinical settings, as in this study, differed from those performed in the classroom in terms of the information gathered about thinking and learning, and the nature of the resulting discourse. These issues were not part of the research focus in this thesis, but were considered in it's design, and it is appropriate to revisit them in the light of the experience of conducting the research.

As in all research, whether quantitative or qualitative, the question of what would

5. as opposed to it's current status as an almost extracurricular activity.

happen with another sample[6] (in the case of quantitative research), or in another context (in the case of qualitative research) is commonly unresolved. As White (1988, p.16) notes, the language of experimental research has been frequently couched in a way that justifies conclusions about the statistical processes employed, without necessarily relating such conclusions to the reality and 'meaning' of such findings. Similarly, Leininger (1994, p.96) notes that '... qualitative researchers should not rely on the use of quantitative criteria such as validity and reliability to explain or justify their findings. Such reliance reflects a lack of knowledge of the different purposes, goals, and philosophical assumptions of the two paradigms.' The non-experimental[7] nature of the research makes addressing these concerns problematic in terms of developing statistically significant conclusions, and they are therefore presented as the researcher's reflective conclusions about the research.

In terms of the goals of this research, the concerns expressed by Niedderer et. al. (1992) are concretised here, positively, for this research, by what I perceive to be a far richer, and finer-grained, dialogue about gravitational the contexts that I would have expected to observe in classroom situations (cf. Section 5.5.1). For example, the response to Suzie (Section 2.1.1 on page 18), and that in Section 2.1.2, are far less focused on explaining the underlying physics concepts than is, for example, Alex's response to general questions about gravity and projectile motion (Section 7.2.4.2 on page 274), particularly when supported by further elicitation in the subsequent gravitational contexts employed in the interview. Similar

6. i.e., in terms of, say, how reliable and 'meaningful' — in real, not statistical terms (e.g., White, 1988, p.16), are the mean and standard deviation of a particular sample of a larger population.

7. i.e., the absence of a formal control group against which to make statistical comparisons.

observations could be made about the majority of the participants.

Likewise, the lack of intrusion of 'classroom clutter' — classroom management, discipline, writing on the board etc., led, I believe, to a more engaged and focused exposition of the participants' understandings than would probably be found in the classroom. Similarly, the superficial treatment of content (as in Section 2.1.2) was replaced by a more intrusive and demanding expository process, which led, I believe, to a far more revealing exposition than would have occurred in classrooms when presenting this content to students. The decision to use a clinical interview therefore seems to be 'validated' by the rich dialogue that was generated in the interviews — which was 'sufficient' to enable the conduct of the research.

Similarly, it is difficult to support a conclusion about Lemke's concerns. However, again anecdotally, I have never observed such sustained periods of dialogue of a similar nature (to those in the interviews) between teachers and students in the physics classrooms (as discussed above) that I visited as part of practicum supervision during the period 1990 - 1997. It is therefore perhaps a reasonable conclusion that, at least, the clinical interview generated data that was satisfactory for the research per se, and which might also approximate to that expected (or hoped) to be observed in classrooms.

9.4.2 The research instruments

The use of the FCI, while very useful as a means of diagnosis and classification, did not particularly assist in the elicitation of the participants' detailed understandings of the gravity contexts examined in Chapter 7 (cf. Section 7.4). The actual videos and computer-based probes proved capable of eliciting (in some cases), quite detailed responses about the events (real or otherwise) depicted in them, showing the value of Haye's suggestion of 'suspending reality' (Hayes, 1979, p.267; Bliss, 1989) in order to get beyond a kind of stimulus-response mode by forcing students to engage with new, perhaps challenging, contexts in explaining their understandings. I believe that the data gathered through the use of such items was, in fact, far richer than that which might have been gathered through the use of a computational approach using StarLogo (as discussed in Chapter 5), where algorithmic representations of understanding would presumably have been developed. In particular, I suspect that the participants' descriptions of events was far more likely to relate to the actual discourse used in classrooms than would that developed from StarLogo (cf. Roschelle, 1991).

In terms of the conduct of the interviews, the decision to attempt to generate 'classroom discourse' rather than to follow the threads of issues to their ultimate cognitive origins (Section 5.5.1) proved to be relatively successful in identifying a range of conceptual difficulties, but left unresolved their explicit cognitive origins (which was not the aim of this research). For the purposes of this thesis, this was a satisfactory outcome, as it was the nature and range of problems with Newtonian force and gravity that was of interest, rather than their explicit, detailed nature. Clearly, following cognitive issues in a threaded way could have led to deeper understandings of the participants' cognitive problems, but was unlikely, in the context of the interview, and the constraints on it (as in Chapter 5), to have allowed such a wide range of contexts to be explored in the time available.

9.5 PCK-enhanced software

The issues discussed in Chapter 8 suggest that the development of PCK-enhanced software is not a conceptually difficult task, but rather, one rooted in Murray's (1996, p.235) point about the difficulty in capturing and describing expert practice in a field (such as Education) that is not based around a structured knowledge domain such as Newtonian mechanics.

As I have argued in Chapter 8, a potentially useful and perhaps realistic approach might be to focus more on the attributes of the posited PCK-agent, and through the use of proven artificial intelligence methods, allow for it's incremental development of expertise (presumably through the use of neural nets and expert systems). Adele provided an example of how tantalisingly real the development of such agents is — if only one could describe and capture teaching knowledge and skills.

Through the conduct of the work for this thesis, I have come to believe that software such as the PCK-enhanced software described herein will eventually come to fruition, though certainly not in the immediate future, and certainly not by being fully preprogrammed with 'the knowledge' as if it were an ITS of the current genre. Instead, such software may need to be considered in somewhat the same way that we view preservice teachers — something that will get better over time through exposure to classroom learning situations, and which may, fancifully, need a practicum of it's own to develop such craft skills as need to be captured.

9.6 Hestenes' Software curriculum

This remains a long term prospect. It's fundamental problem is that it, ultimately, presents a technocentric view of how to address contemporary problems in science education, and does not appear to consider the human, political, and philosophical frameworks in which it is situated. In a sense, Hestenes' call for such a revolutionary overhaul of science education suggests an underlying problem, such as those at the root of the 'crisis' of science education in the 1980's (as discussed in Chapter 2), but which, in fact, may have far more to do with pedagogy and effective teaching models — i.e, PCK, than with the issues of personal, social, and societal relevance that underpinned the previous crisis.

The effective integration of software into educational settings, whether a traditional one, or Hestenes' radical suggestion, depend heavily on the educational philosophies that such use is embedded in, and consequent notions of quality teaching and effective use. Recent guidelines (Niess & Lederman, 2000) for the use of technology in science education emphasize the need to determine the nature and purpose of the use of technology in education (and specifically, science and mathematics education). Hestenes' notion requires further articulation in regard to the issues above, before it is likely to be able to be concretised or implemented. The notion of PCK-enhanced software (as developed in this thesis), however, may be something that can be gradually introduced into science education as advances in artificial intelligence permit, as it is a more incremental, as opposed to revolutionary, approach to addressing concerns about science education — particularly those described in Chapter 2 about the classroom competencies of preservice science teachers.

9.7 Directions for future research

The restructuring of science education pedagogy[8] to focus on the development of *expertise*, rather than on the acquisition of subject matter *knowledge*, (as discussed in Chapter 8) would appear to be a valuable focus for future science education research — one that seems to be consistent with, but different from, the concerns that led to Hestenes' call for a software curriculum for science education.

The role of PCK-enhanced software in such a programme is clear; it would be a platform for concretising, representing, and validating efforts to capture and articulate such expertise (which is no easy task). However, in so doing, there are a number of significant impediments with the technology alone, let alone the descriptive frameworks that could describe such complex knowledge (cf. OntoLingua). The four items listed below are considered to be areas in which significant research has to occur before meaningful progress in the development of software of the type presented in this thesis, and related (undetermined) forms of PCK-enhanced software can be developed:

- What is the nature of a descriptive language that can adequately describe the complex interactions between knowledge elements that seems to characterise expertise?
- What kinds of observational programmes or other kinds of data collection (and their validation) are capable of generating data to be incorporated in the relevant description of expertise (i.e., as above).

8. i.e., at least, in the context of the participants, and hopefully in the wider community of science educators.

- How can we capture and replicate expertise in software? Will advances in Brain Science allow us to 'download' a brain into a Neural Net? In particular, how will the idiosyncratic implementations of expertise (i.e., between expert teachers) be accommodated — or will there be 'only one'?
- What are the implications for 'dehumanising' teaching in this way?[9]

While these are, at one level, 'simple' questions, they are also fundamental ones, and have no easy answers. It is tempting to regard the first three as constituting the 'Holy grail' of the field of artificial intelligence — because they present fundamental challenges to AI researchers and developers. The fourth arises from a need to focus on the wider role of education in society - what kinds of educational experiences does society want for it's children, what values inform it's use, and what *is* the role of a scientific education — to develop a select priesthood (as with the Babylonians mentioned in Chapter 2, or a technologically informed, human-centred society? If it is the latter, then much thinking about the possible human and societal impacts of a (potential) technologically delivered education has to occur, lest Papert's cautions of technocentric thinking come to fruition in ways that he may never have foreseen.

9.8 Personal reflections

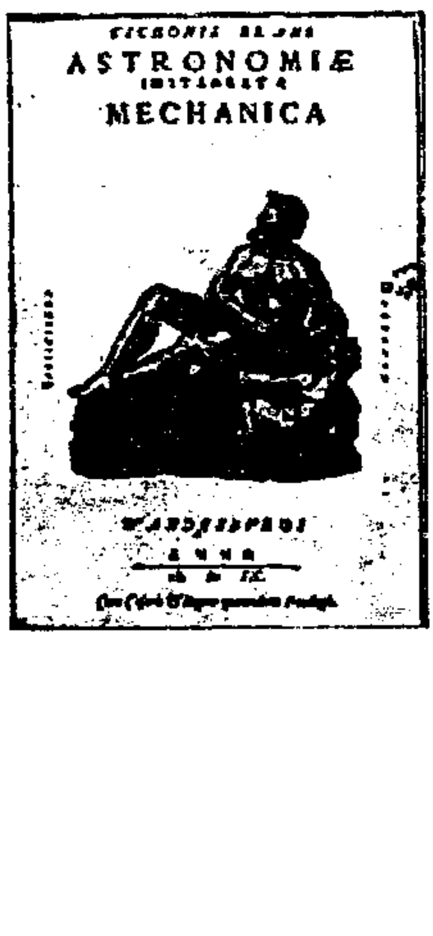
The research conducted for this thesis has had a significant impact on both my teaching, and my understanding of the difficulties of learning to teach. In terms of my teaching, it has led to major changes in both pedagogy and the kinds of

9. Perhaps this is a question situated in the author's context, as there is significant anecdotal evidence to suggest that younger learners are able to accommodate the central use of computers in educational roles.

experiences that students are exposed to. Such changes include adopting a learner-centered learning model, in which reflection and metacognition are encouraged and scaffolded by software — MetaMaps (Nicholson,1995,1998; Nicholson & Johnson, 1999) — that were created specifically for this purpose, coming out of the early ideas that developed during struggling with notions of how elements of PCK might be represented in software, and collaborative on-line environments for sharing ideas and emerging understandings (Nicholson, 1999). Elements of these are to be found in Chapter 8, where they have been related to the PCK-enhanced software model.

Overall, this thesis has provided me with a means of synthesising a disparate range of interests into a cohesive and integrative focus — PCK-enhanced software, it's design, development, and implementation — which form the basis of a long term research plan that I look forward to undertaking.

Appendices



A.1 VCE Physics Unit 4, Area 2, details.

The VCE physics curriculum for the area of study on gravity is listed below. This version existed at the commencement of the study. Minor changes and emphasis have occurred since that time, but the content and emphasis is essentially the same.

A.1.1 Unit Description

Unit 4: motion, gravity, structures, light, & matter

This unit is designed to enable students to:

(a) develop a qualitative and quantitative understanding of physics ideas relating to motion, gravity, structures and use materials, and the nature of light and matter.

(b) Use these ideas to:

- understand and interpret items from the media,
- explain relevant phenomena and events, and technological and social applications,
- develop practical skills in investigating physical phenomena,
- develop familiarity and experience with the ways in which knowledge in physics develops and is used,
- carry out a research project in physics using library and other resources,
- develop the confidence and skills to communicate their knowledge of physics effectively.

Area of study 2 – Gravity: Central Ideas

Newton's insights into gravity have led to understanding of the motion of the Solar System, the achievements of space travel, and satellite technology.

Table A-1: items in the area of study:

1. Newton's law of universal gravitation $F = GM_1M_2/r^2$
2. circular orbits under gravity (using $a = v^2/r = 4\pi^2r/T^2$, comparison with non-circular motion using straightforward energy concepts)
3. energy transfers from area under force-distance graphs
4. gravitational field ($g = G\,M/r^2$)
5. weight, apparent weight (mass and weight as measured by the normal reaction N, experience of weightlessness when $N = 0$)

(NOT required: formula for gravitational potential energy, concept of gravitational potential).

These ideas should be used to explore the context below.

Context: Around the Solar System

Examples: freefall, planetary and lunar motion; artificial satellites of Earth; natural satellites of other planets; geo-stationary satellites; comets; tides; space probes; the validity of science-fiction scenarios.

A.2 Participant science background

The following tables list the participants' engagement with science subjects at school (as a separate specialist subject) and at University. An entry of '0' in these tables means that the subject has not been studied as a separate specialist subject

Table A-2: Joanna - science background.

Science subject	University level	School level[a]
Biology	0[b]	12
Chemistry	0	11
Earth sciences	2	11
Environmental science	0	10
Physics	3	12
Other	4 (Mathematics)	

a. as a separate specialist study.
b. an entry of '0' in these tables means that the subject has not been studied as a specialist subject.

Table A-3: Susan - science background.

Science subject	University level	School level
Biology	1	12
Chemistry	1	11
Earth sciences	0	0
Environmental science	0	0
Physics	3	11
Other relevant subjects	4 (Mathematics)	

Table A-4: Denise - science background.

Science subject	University level	School level
Biology	1	11
Chemistry	0	12
Earth sciences	0	0
Environmental science	0	0
Physics	3	12
Other relevant subjects	4 (Mathematics)	

Table A-5: Alex - science background.

Science subject	University level	School level
Biology	0	11
Chemistry	0	12
Earth sciences	2	0
Environmental science	0	0
Physics	3	12
Other relevant subjects	3 (Mathematics)	

Table A-6: Jim - science background.

Science subject	University level	School level
Biology	3	11
Chemistry	0	12
Earth sciences	0	0
Environmental science	0	0
Physics	3	12
Other relevant subjects	3 (Mathematics)	

Table A-7: Joe - science background.

Science subject	University level	School level
Biology	1[a]	12
Chemistry	0	0
Earth sciences	0	0
Environmental science	0	0
Physics	3	12
Other relevant subjects	3 (Mathematics)	

a. at the time of the interview, Joe was undertaking studies in second-year Biology,

Table A-8: James - science background.

Science subject	University level	School level
Biology	3	12
Chemistry	0	11
Earth sciences	0	0
Environmental science	0	0
Physics	3	12
Other relevant subjects	3 (Sociology)	

Table A-9: Steve - science background.

Science subject	University level	School level
Biology	0	12
Chemistry	0	11
Earth sciences	0	0
Environmental science	0	0
Physics	4	12
Other relevant subjects	4 (Physical Education)	

Table A-10: Alan - science background.

Science subject	University level	School level
Biology	1	11
Chemistry	3	12
Earth sciences	1	0
Environmental science	0	0
Physics	3	12
Other relevant subjects		

Table A-11: Anne - science background.

Science subject	University level	School level
Biology	0	10
Chemistry	1	11
Earth sciences	1	0
Environmental science	0	0
Physics	3	12
Other relevant subjects	3 (English, Literature)	

Table A-12: Helen - science background.

Science subject	University level	School level
Biology	1	12
Chemistry	0	11
Earth sciences	0	0
Environmental science	0	0
Physics	3	12
Other relevant subjects	4 (Mathematics)	

Force Concept Inventory

Please:

Do not write anything on this questionnaire.

Mark your answers on the ParSCORE computer sheet.

Make only one mark per item.

Do not skip any question.

Avoid guessing. Your answers should reflect what you personally think.

On the ParSCORE computer sheet:

Use a No. 2 pencil only, and follow marking instructions.

Fill in your ID number. This is the number given to you by your school or your teacher.

Mark "1" under "Test Form".

Fill in the "Exam No." given by your teacher.

Plan to finish this questionnaire in 30 minutes.

Thank you for your cooperation.

A.3 The Force Concept Inventory

1. Two metal balls are the same size but one weighs twice as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. The time it takes the balls to reach the ground below will be:
   (A) about half as long for the heavier ball as for the lighter one.
   (B) about half as long for the lighter ball as for the heavier one.
   (C) about the same for both balls.
   (D) considerably less for the heavier ball, but not necessarily half as long.
   (E) considerably less for the lighter ball, but not necessarily half as long.

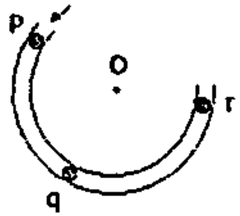
2. The two metal balls of the previous problem roll off a horizontal table with the same speed. *In this situation:*
   (A) both balls hit the floor at approximately the same horizontal distance from the base of the table.
   (B) the heavier ball hits the floor at about half the horizontal distance from the base of the table than does the lighter ball.
   (C) the lighter ball hits the floor at about half the horizontal distance from the base of the table than does the heavier ball.
   (D) the heavier ball hits the floor considerably closer to the base of the table than the lighter ball, but not necessarily at half the horizontal distance.
   (E) the lighter ball hits the floor considerably closer to the base of the table than the heavier ball, but not necessarily at half the horizontal distance.

3. A stone dropped from the roof of a single story building to the surface of the earth:
   (A) reaches a maximum speed quite soon after release and then falls at a constant speed thereafter.
   (B) speeds up as it falls because the gravitational attraction gets considerably stronger as the stone gets closer to the earth.
   (C) speeds up because of an almost constant force of gravity acting upon it.
   (D) falls because of the natural tendency of all objects to rest on the surface of the earth.
   (E) falls because of the combined effects of the force of gravity pushing it downward and the force of the air pushing it downward.

4. A large truck collides head-on with a small compact car. During the collision:
   (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 gets in the way of the truck.
   (D) the truck exerts a force on the car but the car does not 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.

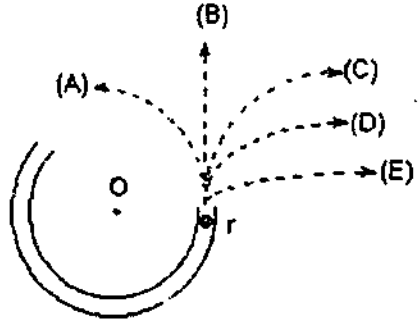
USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT TWO QUESTIONS (5 and 6).

The accompanying figure shows a frictionless channel in the shape of a segment of a circle with center at "O". The channel has been anchored to a frictionless horizontal table top. You are looking down at the table. Forces exerted by the air are negligible. A ball is shot at high speed into the channel at "p" and exits at "r."



5. Consider the following distinct forces:
   1. A downward force of gravity.
   2. A force exerted by the channel pointing from q to O.
   3. A force in the direction of motion.
   4. A force pointing from O to q.

   Which of the above forces is (are) acting on the ball when it is within the frictionless channel at position "q"?
   (A) 1 only.
   (B) 1 and 2.
   (C) 1 and 3.
   (D) 1, 2, and 3.
   (E) 1, 3, and 4.

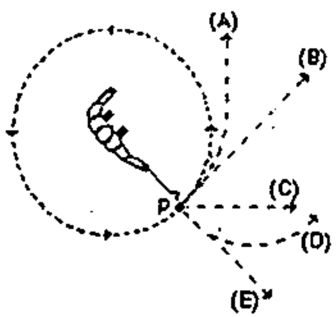


6. Which path in the figure at right would the ball most closely follow after it exits the channel at "r" and moves across the frictionless table top?

7. A steel ball is attached to a string and is swung in a circular path in a horizontal plane as illustrated in the accompanying figure.

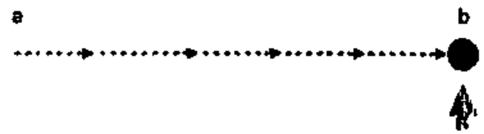
   At the point P indicated in the figure, the string suddenly breaks near the ball.

   If these events are observed from directly above as in the figure, which path would the ball most closely follow after the string breaks?

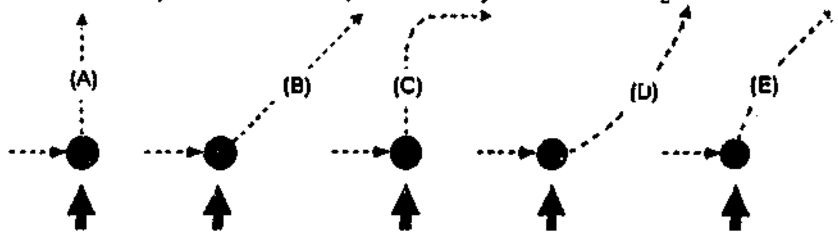


USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT FOUR QUESTIONS (8 through 11).

The figure depicts a hockey puck sliding with constant speed v_o in a straight line from point "a" to point "b" on a frictionless horizontal surface. Forces exerted by the air are negligible. You are looking down on the puck. When the puck reaches point "b," it receives a swift horizontal kick in the direction of the heavy print arrow. Had the puck been at rest at point "b," then the kick would have set the puck in horizontal motion with a speed v_k in the direction of the kick.



8. Which of the paths below would the puck most closely follow after receiving the kick?

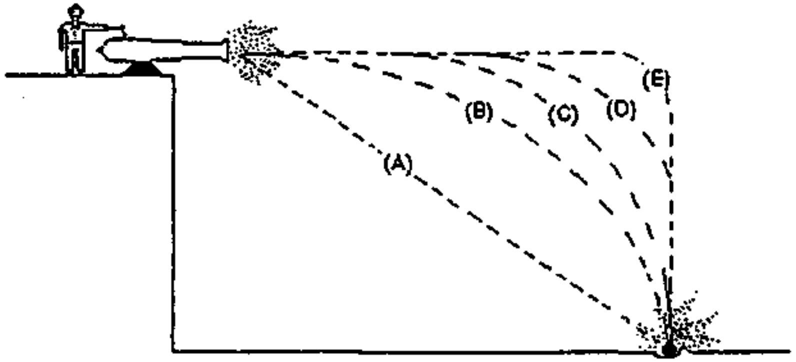


9. The speed of the puck just after it receives the kick is:
   (A) equal to the speed "v_o" it had before it received the kick.
   (B) equal to the speed "v_k" resulting from the kick and independent of the speed "v_o".
   (C) equal to the arithmetic sum of the speeds "v_o" and "v_k".
   (D) smaller than either of the speeds "v_o" or "v_k".
   (E) greater than either of the speeds "v_o" or "v_k", but less than the arithmetic sum of these two speeds.

10. Along the frictionless path you have chosen in question 8, the speed of the puck after receiving the kick:
    (A) is constant.
    (B) continuously increases.
    (C) continuously decreases.
    (D) increases for a while and decreases thereafter.
    (E) is constant for a while and decreases thereafter.

11. Along the frictionless path you have chosen in question 8, the main force(s) acting on the puck after receiving the kick is (are):
    (A) a downward force of gravity.
    (B) a downward force of gravity, and a horizontal force in the direction of motion.
    (C) a downward force of gravity, an upward force exerted by the surface, and a horizontal force in the direction of motion.
    (D) a downward force of gravity and an upward force exerted by the surface.
    (E) none. (No forces act on the puck.)

12. A ball is fired by a cannon from the top of a cliff as shown in the figure below. Which of the paths would the cannon ball most closely follow?



13. A boy throws a steel ball straight up. Consider the motion of the ball only after it has left the boy's hand but before it touches the ground, and assume that forces exerted by the air are negligible. For these conditions, the force(s) acting on the ball is (are):

(A) a downward force of gravity along with a steadily decreasing upward force.

(B) a steadily decreasing upward force from the moment it leaves the boy's hand until it reaches its highest point; on the way down there is a steadily increasing downward force of gravity as the object gets closer to the earth.

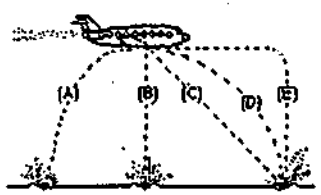
(C) an almost constant downward force of gravity along with an upward force that steadily decreases until the ball reaches its highest point; on the way down there is only a constant downward force of gravity.

(D) an almost constant downward force of gravity only.

(E) none of the above. The ball falls back to ground because of its natural tendency to rest on the surface of the earth.

14. A bowling ball accidentally falls out of the cargo bay of an airliner as it flies along in a horizontal direction.

As observed by a person standing on the ground and viewing the plane as in the figure at right, which path would the bowling ball most closely follow after leaving the airplane?



USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT TWO QUESTIONS (15 and 16).

A large truck breaks down out on the road and receives a push back into town by a small compact car as shown in the figure below.

15. While the car, still pushing the truck, is speeding up to get up to cruising speed:

(A) the amount of force with which the car pushes on the truck is equal to that with which the truck pushes back on the car.

(B) the amount of force with which the car pushes on the truck is smaller than that with which the truck pushes back on the car.

(C) the amount of force with which the car pushes on the truck is greater than that with which the truck pushes back on the car.

(D) the car's engine is running so the car pushes against the truck, but the truck's engine is not running so the truck cannot push back against the car. The truck is pushed forward simply because it is in the way of the car.

(E) neither the car nor the truck exert any force on the other. The truck is pushed forward simply because it is in the way of the car.

16. After the car reaches the constant cruising speed at which its driver wishes to push the truck:

(A) the amount of force with which the car pushes on the truck is equal to that with which the truck pushes back on the car.

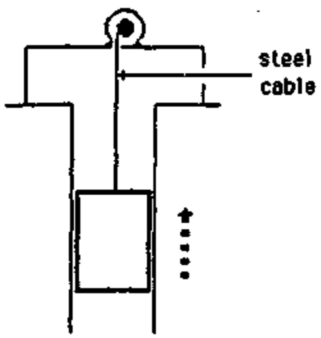
(B) the amount of force with which the car pushes on the truck is smaller than that with which the truck pushes back on the car.

(C) the amount of force with which the car pushes on the truck is greater than that with which the truck pushes back on the car.

(D) the car's engine is running so the car pushes against the truck, but the truck's engine is not running so the truck cannot push back against the car. The truck is pushed forward simply because it is in the way of the car.

(E) neither the car nor the truck exert any force on the other. The truck is pushed forward simply because it is in the way of the car.

17. An elevator is being lifted up an elevator shaft at a constant speed by a steel cable as shown in the figure below. All frictional effects are negligible. In this situation, forces on the elevator are such that:
   (A) the upward force by the cable is greater than the downward force of gravity.
   (B) the upward force by the cable is equal to the downward force of gravity.
   (C) the upward force by the cable is smaller than the downward force of gravity.
   (D) the upward force by the cable is greater than the sum of the downward force of gravity and a downward force due to the air.
   (E) none of the above. (The elevator goes up because the cable is being shortened, not because an upward force is exerted on the elevator by the cable).

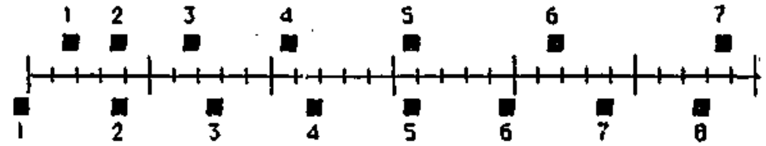


Elevator going up at constant speed

18. The figure below shows a boy swinging on a rope, starting at a point higher than A.
Consider the following distinct forces:
   1. A downward force of gravity.
   2. A force exerted by the rope pointing from A to O.
   3. A force in the direction of the boy's motion.
   4. A force pointing from O to A.

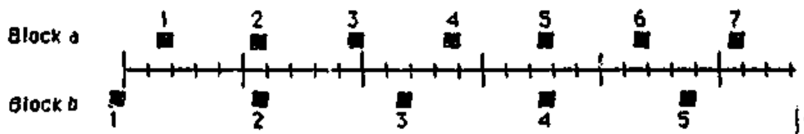
Which of the above forces is (are) acting on the boy when he is at position A?
   (A) 1 only.
   (B) 1 and 2.
   (C) 1 and 3.
   (D) 1, 2, and 3.
   (E) 1, 3, and 4.

19. The positions of two blocks at successive 0.20-second time intervals are represented by the numbered squares in the figure below. The blocks are moving toward the right.



Do the blocks ever have the same speed?
   (A) No.
   (B) Yes, at instant 2.
   (C) Yes, at instant 5.
   (D) Yes, at instants 2 and 5.
   (E) Yes, at some time during the interval 3 to 4.

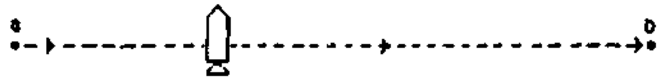
20. The positions of two blocks at successive 0.20-second time intervals are represented by the numbered squares in the figure below. The blocks are moving toward the right.



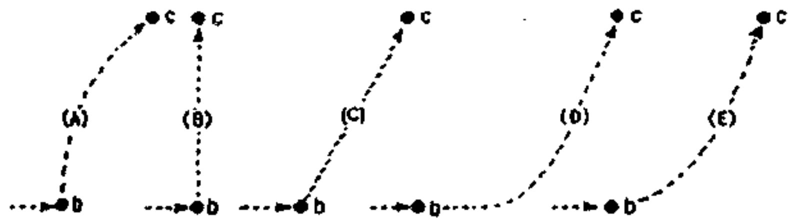
The accelerations of the blocks are related as follows:
   (A) The acceleration of "a" is greater than the acceleration of "b".
   (B) The acceleration of "a" equals the acceleration of "b". Both accelerations are greater than zero.
   (C) The acceleration of "b" is greater than the acceleration of "a".
   (D) The acceleration of "a" equals the acceleration of "b". Both accelerations are zero.
   (E) Not enough information is given to answer the question.

USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT FOUR QUESTIONS (21 through 24).

A rocket drifts sideways in outer space from point "a" to point "b" as shown below. The rocket is subject to no outside forces. Starting at position "b", the rocket's engine is turned on and produces a constant thrust (force on the rocket) at right angles to the line "ab". The constant thrust is maintained until the rocket reaches a point "c" in space.

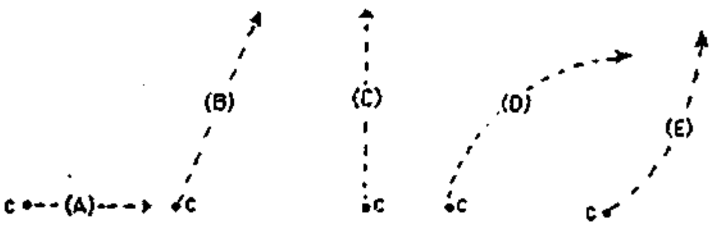


21. Which of the paths below best represents the path of the rocket between points "b" and "c"?



22. As the rocket moves from position "b" to position "c" its speed is:
    (A) constant.
    (B) continuously increasing.
    (C) continuously decreasing.
    (D) increasing for a while and constant thereafter.
    (E) constant for a while and decreasing thereafter.

23. At point "c" the rocket's engine is turned off and the thrust immediately drops to zero. Which of the paths below will the rocket follow beyond point "c"?



24. Beyond position "c" the speed of the rocket is:
    (A) constant.
    (B) continuously increasing.
    (C) continuously decreasing.
    (D) increasing for a while and constant thereafter.
    (E) constant for a while and decreasing thereafter.

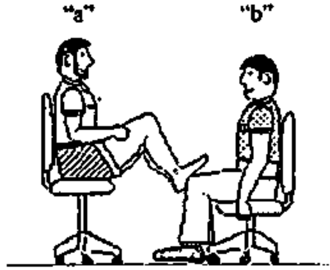
25. A woman exerts a constant horizontal force on a large box. As a result, the box moves across a horizontal floor at a constant speed "v_o".
    The constant horizontal force applied by the woman:
    (A) has the same magnitude as the weight of the box.
    (B) is greater than the weight of the box.
    (C) has the same magnitude as the total force which resists the motion of the box.
    (D) is greater than the total force which resists the motion of the box.
    (E) is greater than either the weight of the box or the total force which resists its motion.

26. If the woman in the previous question doubles the constant horizontal force that she exerts on the box to push it on the same horizontal floor, the box then moves:
    (A) with a constant speed that is double the speed "v_o" in the previous question.
    (B) with a constant speed that is greater than the speed "v_o" in the previous question, but not necessarily twice as great.
    (C) for a while with a speed that is constant and greater than the speed "v_o" in the previous question, then with a speed that increases thereafter.
    (D) for a while with an increasing speed, then with a constant speed thereafter.
    (E) with a continuously increasing speed.

27. If the woman in question 25 suddenly stops applying a horizontal force to the box, then the box will:
    (A) immediately come to a stop.
    (B) continue moving at a constant speed for a while and then slow to a stop.
    (C) immediately start slowing to a stop.
    (D) continue at a constant speed.
    (E) increase its speed for a while and then start slowing to a stop.

28. In the figure at right, student "a" has a mass of 95 kg and student "b" has a mass of 77 kg. They sit in identical office chairs facing each other.

Student "a" places his bare feet on the knees of student "b", as shown. Student "a" then suddenly pushes outward with his feet, causing both chairs to move.



During the push and while the students are still touching one another:

(A) neither student exerts a force on the other.
(B) student "a" exerts a force on student "b", but "b" does not exert any force on "a".
(C) each student exerts a force on the other, but "b" exerts the larger force.
(D) each student exerts a force on the other, but "a" exerts the larger force.
(E) each student exerts the same amount of force on the other.

29. An empty office chair is at rest on a floor. Consider the following forces:

1. A downward force of gravity.
2. An upward force exerted by the floor.
3. A net downward force exerted by the air.

Which of the forces is (are) acting on the office chair?

(A) 1 only.
(B) 1 and 2.
(C) 2 and 3.
(D) 1, 2, and 3.
(E) none of the forces. (Since the chair is at rest there are no forces acting upon it.)

30. Despite a very strong wind, a tennis player manages to hit a tennis ball with her racquet so that the ball passes over the net and lands in her opponent's court.
Consider the following forces:

1. A downward force of gravity.
2. A force by the "hit".
3. A force exerted by the air.

Which of the above forces is (are) acting on the tennis ball after it has left contact with the racquet and before it touches the ground?

(A) 1 only.
(B) 1 and 2.
(C) 1 and 3.
(D) 2 and 3.
(E) 1, 2, and 3.

Force Concept Inventory

The *Force Concept Inventory* (FCI) is a multiple-choice "test" designed to assess student understanding of the *most basic* concepts in Newtonian mechanics. The FCI can be used for several different purposes, but the most important one is to evaluate the effectiveness of instruction. For a full understanding of what has gone into the development of this instrument and how it can be used, the FCI papers[1,2] should be consulted, as well as: (a) the papers on the Mechanics Diagnostic Test[3,4], the FCI predecessor, (b) the paper on the Mechanics Baseline Test[5] which is recommended as an FCI companion test for assessing quantitative problem-solving skills, and (c) Richard Hake's[6] data collection on university and high school physics taught by many different teachers and methods across the USA.

References

1. David Hestenes, Malcolm Wells, & Gregg Swackhamer (1992). Force Concept Inventory, *The Physics Teacher*, 30 (3), 141-151.
2. David Hestenes & Ibrahim Halloun (1995). Interpreting the Force Concept Inventory, *The Physics Teacher*, 33 (8), 502, 504-506.
3. Ibrahim Halloun & David Hestenes (1985). The initial knowledge state of college physics students, *American Journal of Physics*, 53 (11), 1043-1055.
4. Ibrahim Halloun & David Hestenes (1985). Common sense concepts about motion, *American Journal of Physics*, 53 (11), 1056-1065.
5. David Hestens & Malcolm Wells (1992). A Mechanics Baseline Test, *The Physics Teacher*, 30 (3), 159-166.
6. Richard Hake (1994, August). Survey of Test Data for Introductory Mechanics Courses, *AAPT Announcer*, 24 (2), 55.

A.4 Details of the computer probes

A.4.1 Projectile probe

The probe was produced as a QuickTime™ movie (Apple Computer, 1996), with MooVer™ (Schwan, 1995) being used to combine a series of images produced by LCSI MicroWorlds™ (Silvermann, 1993). The resulting stand-alone document was portable between Macintosh and IBM-compatible computers and World Wide Web pages. The was important as the delivery platform had not been decided upon at the time the probes were created. Participants were able to review the motion by moving forward and back in the probe by using the Quicktime viewer slider control.

A.4.2 3D Rotater™ probes

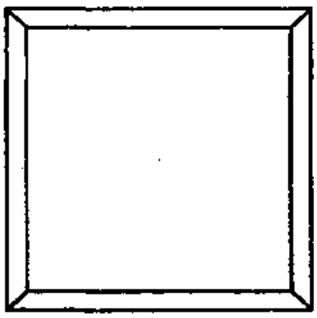
The probes were constructed using Rotater™ (Kloeden, 1995) which creates computer-based representations of objects that can be rotated around three orthogonal axes by dragging the image with a computer's 'mouse cursor'. Perspective, zooming, and stereoscopic options provide enhanced viewing for visualising complex three-dimensional objects. Programs consist of a tab-delimited text file which lists the X,Y,Z coordinates of the points to be displayed, and their colour. The appearance of lines and points in the final image may be configured dynamically. In this study, visual cluing was provided by a bounding box with uniquely coloured edges delimiting the volume of space.

These probes consist of three dimensional cubes which can be rotated and spun using the computer's mouse. This enables the user to inspect the path of the particles contained within them from any angle they so desire. The series of probes below employs a common cube model, the source code of which is listed below. The code listed below for each individual probe is that which is solely related to drawing the particle paths within each cube. The program text files have the format X_{pos}, Y_{pos}, Z_{pos}, colour, so that the position and colour of points and lines can easily be set. Table A-1 lists the common code for the wire-frame cube that is common to each of these probes. This code is inserted at the point in the following listings labelled "Insert cube code here".

Program A-1: Common cube frame code.

```
#DRAW COMMON CUBE FRAME
# Draw first face
 1  -1  -1  1
-1  -1  -1  1
-1   1  -1  1
 1   1  -1  1
 1   1   1  3
# Draw second face
 1  -1   1  2
-1  -1   1  2
-1   1   1  2
 1   1   1  2
# Join faces with lines
-1  -1  -1  0
-1  -1   1  3
-1   1  -1  0
-1   1   1  3
 1  -1  -1  0
 1  -1   1  3
```

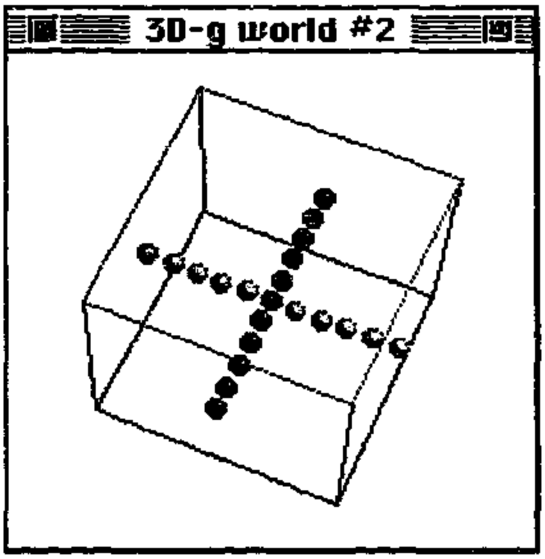
Figure A-1: Common cube used by all probes.

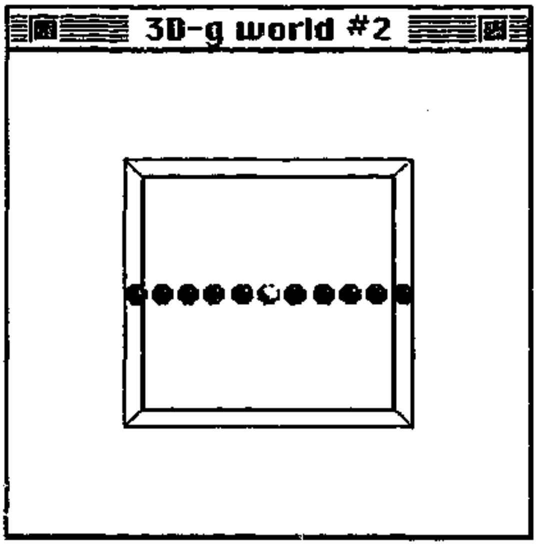


Program A-2: World 2 source code.

```
#3D gravity space
#by Paul Nicholson
#WORLD NUMBER 2
#SCALES in UNIT CUBE
centered on 0 0 0
# draw motion of particle 1 from
rear to front face in yellow
0.0   1.0  0.0  -4
0.0   0.8  0.0  -4
0.0   0.6  0.0  -4
0.0   0.4  0.0  -4
0.0   0.2  0.0  -4
0.0   0.0  0.0  -4
0.0  -0.8  0.0  -4
0.0  -0.6  0.0  -4
0.0  -0.4  0.0  -4
0.0  -0.2  0.0  -4
0.0  -1.0  0.0  -4
#draw motion of particle 2 from-
left to right face in purple
 1.0   0.0  0.0  -5
 0.8   0.0  0.0  -5
 0.6   0.0  0.0  -5
 0.4   0.0  0.0  -5
 0.2   0.0  0.0  -5
 0.0   0.0  0.0  -5
-0.8   0.0  0.0  -5
-0.6   0.0  0.0  -5
-0.4   0.0  0.0  -5
-0.2   0.0  0.0  -5
-1.0   0.0  0.0  -5
#Insert cube code here
#END
```

Figure A-2: World 2 with two views of the particles' motion.

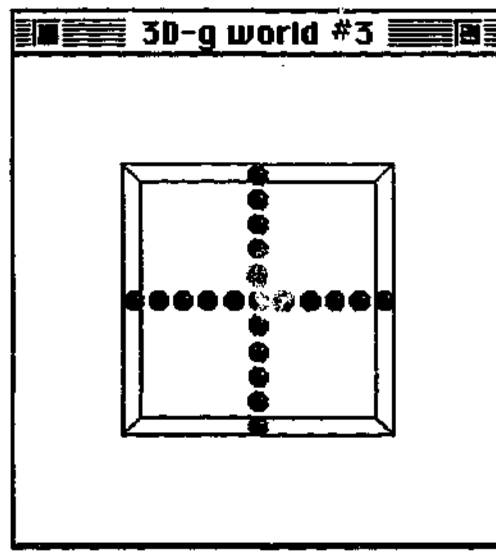


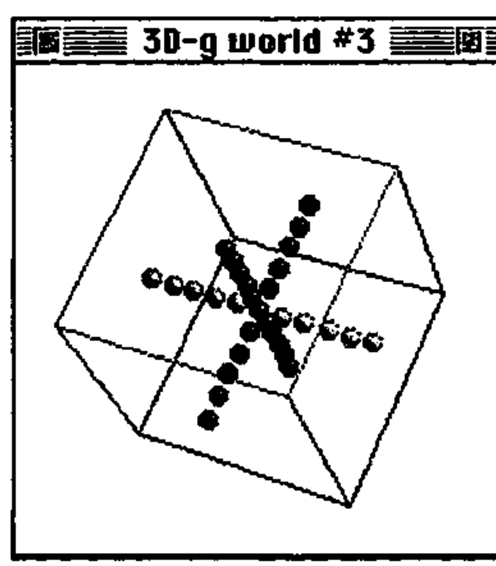


Program A-3: World 3 source code.

```
#3D #WORLD NUMBER 3
#by Paul Nicholson
#SCALES in UNIT CUBE
centered on 0 0 0
#draw motion of particle from
rear to front face in yellow
0  1.0 0 -4
0  0.8 0 -4
0  0.6 0 -4
0  0.4 0 -4
0  0.2 0 -4
0  0.0 0 -4
0 -0.8 0 -4
0 -0.6 0 -4
0 -0.4 0 -4
0 -0.2 0 -4
0 -1.0 0 -4
#draw motion of particle from
left to right face in blue
 1.0 0 0 -5
 0.8 0 0 -5
 0.6 0 0 -5
 0.4 0 0 -5
 0.2 0 0 -5
 0.0 0 0 -5
-0.8 0 0 -5
-0.6 0 0 -5
-0.4 0 0 -5
-0.2 0 0 -5
-1.0 0 0 -5
#draw motion of particle from
left to right face in colour 2
0 0  1.0 -2
0 0  0.8 -2
0 0  0.6 -2
0 0  0.4 -2
0 0  0.2 -2
0 0  0.0 -2
0 0 -0.8 -2
0 0 -0.6 -2
0 0 -0.4 -2
0 0 -0.2 -2
0 0 -1.0 s-2
#Insert cube code here
#END
```

Figure A-3: World 3 with views of the particles' motion.

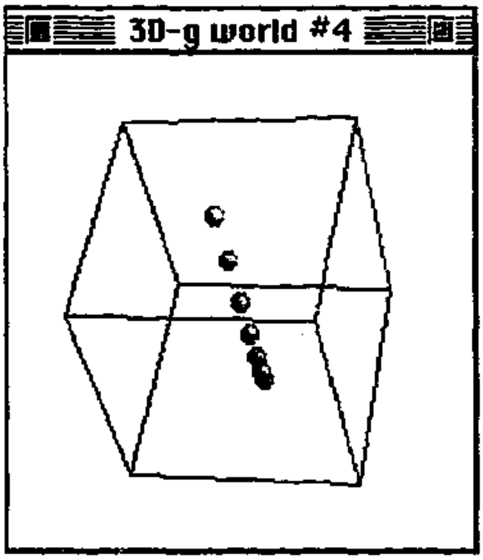




Program A-4: World 4 source code.

```
#3D gravity space
#by Paul Nicholson
#WORLD NUMBER 4
#SCALES in UNIT CUBE
centered on 0 0 0

 0.0  1.00.0-4
 0.0  0.90.0-4
 0.0  0.70.0-4
 0.0  0.40.0-4
 0.0  0.0 0.0 -4
 0.0 -0.50.0-4
 0.0 -1.00.0-4

#Insert cube code here
#END
```

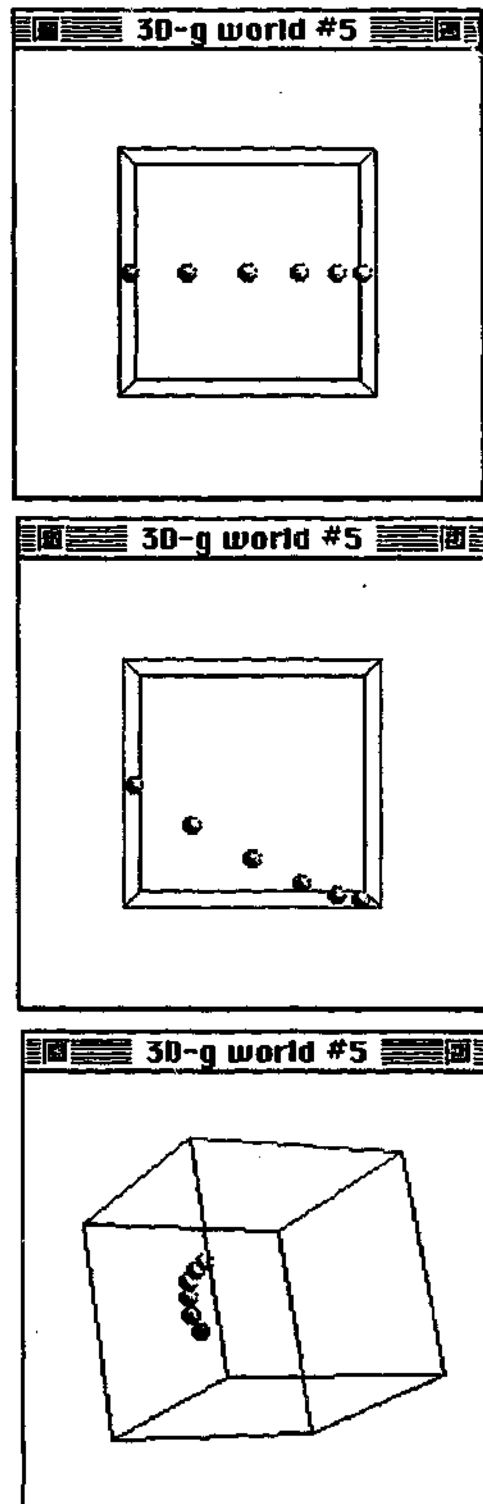
Figure A-4: World 4 with a view of the particle's motion.



Program A-5: World 5 source code.

```
#3D gravity space
#by Paul Nicholson
#WORLD NUMBER 5
#SCALES in UNIT CUBE
centered on 0 0 0
# 2D curved motion

0.99  0.9  0.0 -4
0.95  0.7  0.0 -4
0.85  0.4  0.0 -4
0.65  0.0  0.0 -4
0.35 -0.5  0.0 -4
0.00 -1.0  0.0 -4
#Insert cube code here
# END
```

Figure A-5: World 5 with views of the particle's motion.



A.4.3 StarLogo (field dependence) probes

A.4.3.1. Common Code Elements

The Green-World and Blue-World probes include the three common turtle motions listed below as programs A-6 to A-8. For reasons of clarity, these procedures have been removed from the code and formatted as 'include files' that are inserted at the points labelled in the respective programs as [INC-1], [INC-2] and [INC-3].

The 'Setup' procedure in each listing is manually altered to include the colour of the world, e.g., GREEN-WORLD.PCS, so that in the debugging phase, and production of the QuickTime movies using the snapshot primitive, the data and images are recorded to the appropriate file. Further decomposition of the procedures is possible, but was deemed unnecessary for a program of this size.

The 'Go' procedure was used for testing and development, but not included in the final interface in order to make explicit reference to the three discrete particle paths. While there is no fundamental rationale for this design decision, it seemed intuitively more suitable to focus on the individual particle paths rather than the world as a whole.

Program A-6: Code segment INC-1.

```
To MOVE-1
 CRT 1 SETXY 0 -45 SETC Yellow SETH 0
 REPEAT 10
 [       SNAPSHOT
         STAMP Yellow
         FD 10
         IFELSE(ABS Xcor>(Screen-edge-9)) OR (ABS Ycor>(Screen-edge-9))
         [DIE][WAIT 1] ]
END
```

Program A-7: Code segment INC-2.

```
To MOVE-2
 CRT 1 SETXY -45 0 SETC White SETH 90
 REPEAT 20
 [        SNAPSHOT
          STAMP White
          FD G/5
          IFELSE(ABS Xcor>(Screen-edge-9)) OR (ABS Ycor>(Screen-edge-9))
          [DIE][WAIT 1] ]
END
```

Program A-8: Code segment INC-3.

```
To MOVE-3
 CRT 1 SETXY -45 -45 SETC Red SETH 60
 REPEAT 24
 [      SNAPSHOT
        STAMP Red
        FD G/5
        SETY Ycor + 1
        IFELSE(ABS Xcor>(Screen-edge-9)) OR (ABS Ycor>(Screen-edge-9))
       [DIE][WAIT 1] ]
END
```

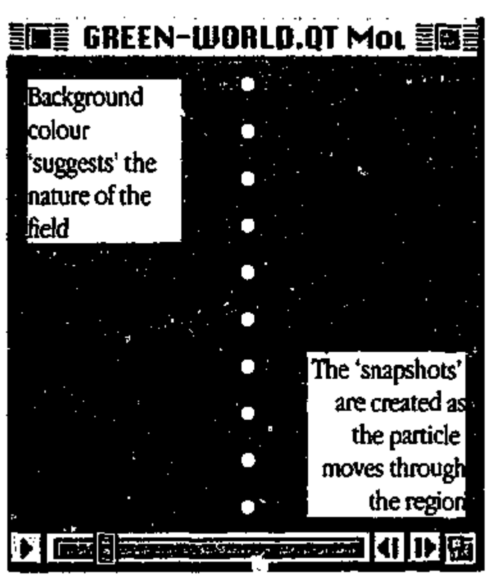
Program A-9: Green World source code.

```
 ;;   GREEN WORLD SOURCE CODE by P. Nicholson
 ;; ------------------------
 patches-own [G direction]
TO GO
 setup
 move-1 move-2 move-3
 finish
END
To SETUP
 Create_Uniform_Field
 Setup-movie "GREEN-WORLD.PCS
END

 [INC-1]
 [INC-2]
 [INC-3]

To FINISH
 close-movie
END
TO CREATE_UNIFORM_FIELD
 ca  SetG 10  setpc green
END
```

Program A-10: Blue World source code.

```
 ;;   BLUE WORLD SOURCE CODE by P.Nicholson
 ;; --------------------------
 Patches-own [G direction]

TO GO
 setup
     move-1   move-2   move-3
 finish
END

TO SETUP
 Create_Horizontal_Field
 setup-movie "BLUE-WORLD.PCS
END

 [INC-1]
 [INC-2]
 [INC-3]
TO FINISH
 Close-Movie
END

TO CREATE_HORIZONTAL_FIELD
 ca
 setdirection  90        ;; object moves left-> right
 SetG 50 + Xcor          ;; linear function of X coordinate.
 scale-pc blue G 1 100   ;; provide visual representation.
END
```

Figure A-6: Basic features of the StarLogo probes.



Program A-11: Red World source code.

```
;; ----------------------------------
;; RED WORLD SOURCE CODE by P.Nicholson
;; USE TO GENERATE QUICKTIME MOVIES FOR PROBES
;; ** NEEDS FIX FOR ALL QUADRANTS TO WORK CORRECTLY **
;; ----------------------------------
patches-own [gravity direction step]
turtles-own [ahead speed X0 y0 x1 y1 ]

TO GO
   SETUP-MOVIE "RED-WORLD.PCS
   REPEAT 200 [ Move Fall Point SnapShot WAIT delay / 10 ]
   CLOSE-MOVIE
END

TO POINT
  SETH towards-nowrap X0 Y0 RT 180 SetAhead heading
END

TO MOVE
   SETH ahead setx0 xcor sety0 ycor
   IFELSE (SPEED / scale) + (DISTANCE 0 0) < 4 [DIE][FD SPEED / scale]
END

TO FALL
   SETH towards-nowrap 0 0
   IFELSE (GRAVITY / scale)+(DISTANCE 0 0) < 4 [DIE][FD GRAVITY / scale]
END

TO G
   OUTPUT Planet/((distance-NOWRAP 0 0)*(distance-NOWRAP 0 0))
END

TO NEWPARTICLE
   CRT Turtles SetShape 27
   PU FD 18 + RANDOM screen-edge
   SETH RANDOM 360
   SetAhead heading SetSpeed 5 + RANDOM 40
END

TO SETUP
   CA
   setgravity G
   SCALE-PC red gravity 1 500
   NewParticle
END
```

Figure A-7: Green World and Blue World interface.

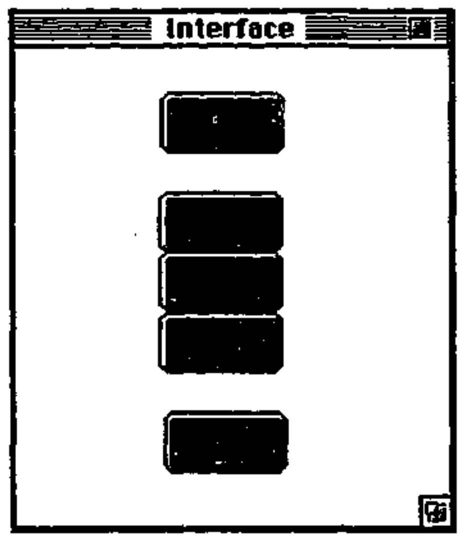
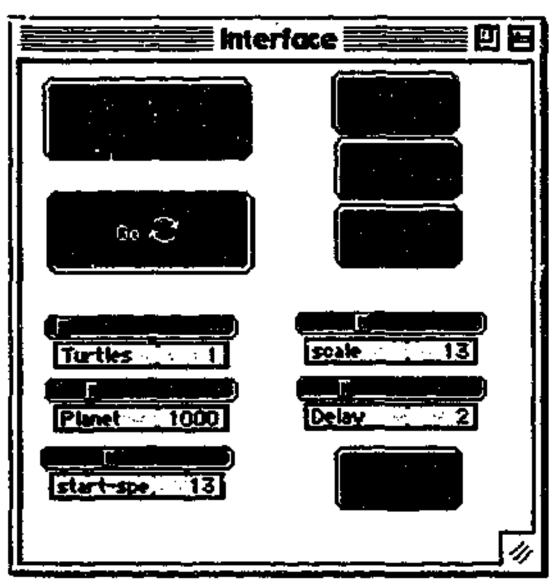


Figure A-8: Red World interface.



A.4.4 The 'GRAVITATION™' planetary probes

This series of probes was created using Gravitation™ versions 4 and 5 (Rommereide, 1988, 1994). The 'Gravitation' probes are created through the use of a dialogue box that specifies the mass, velocity and position of particles in the simulation. Section A.4.4.1. lists the source data for the probes used in this thesis. The actual software and probes are contained on the accompanying CD-ROM, and can be found under the Probes - Gravitation Probes entry. Note that a Macintosh Power PC computer with System 8.0 or later is required to run the software and probes. In probes one to six, the central major particles (planets) are fixed on the screen by designating thm as being stationary in the dialogue box. This was done to provide a first-order approximation to the simulation, in which the effect of gravity on the smaller particles (asteroids) was the prime focus, rather than the much larger gravitational interaction between the planets. In probes seven to ten, however, the planets are able to move under the combined gravitational force of all of the other particles, resulting in complex and potentially confusing motion.

A.4.4.1. Source data for the 'Gravitation' probes

The Gravitation probes setup dialogue box in Figure A-9 shows the controls available in this software. Note that the velocity and position components may be entered directly into the dialogue box or 'created' by dragging the vector representation (for velocity) in the smaller graphic window, or the planet itself (for position) within the larger graphic window.

Figure A-9: Probe G-1 setup A.

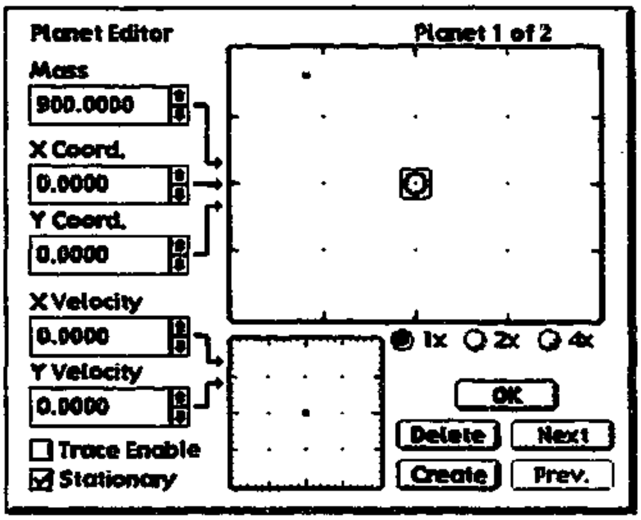


Figure A-10: Probe G-1 setup B.

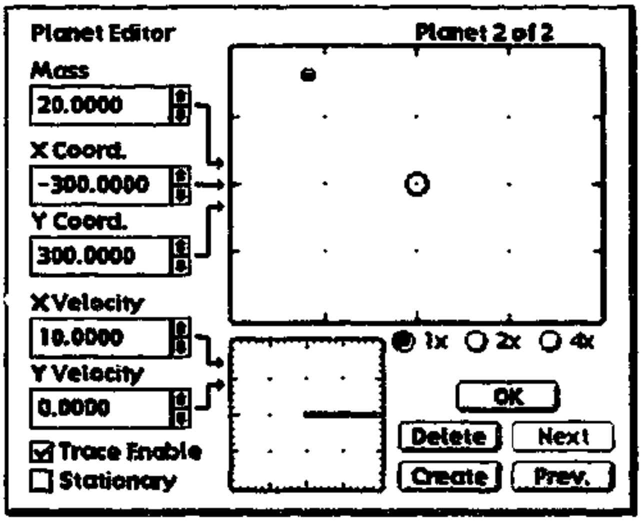


Figure A-11: Probe G-2 setup A.

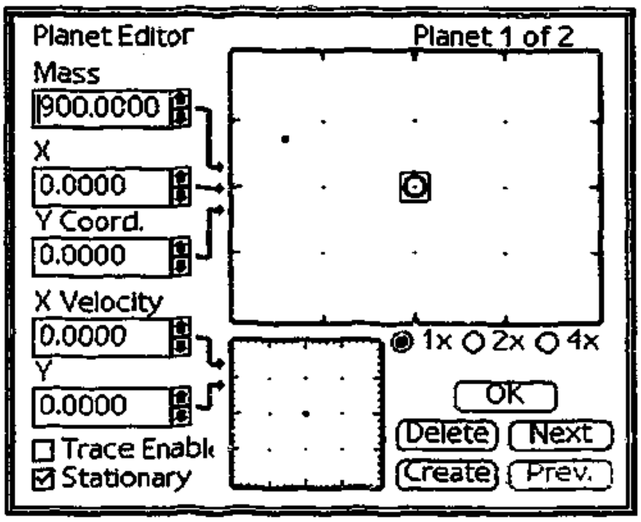


Figure A-12: Probe G-2 setup B.

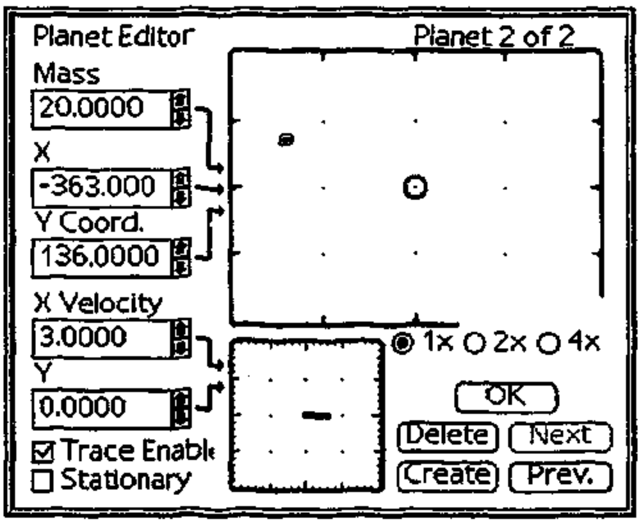


Figure A-13: Probe G-3 setup.

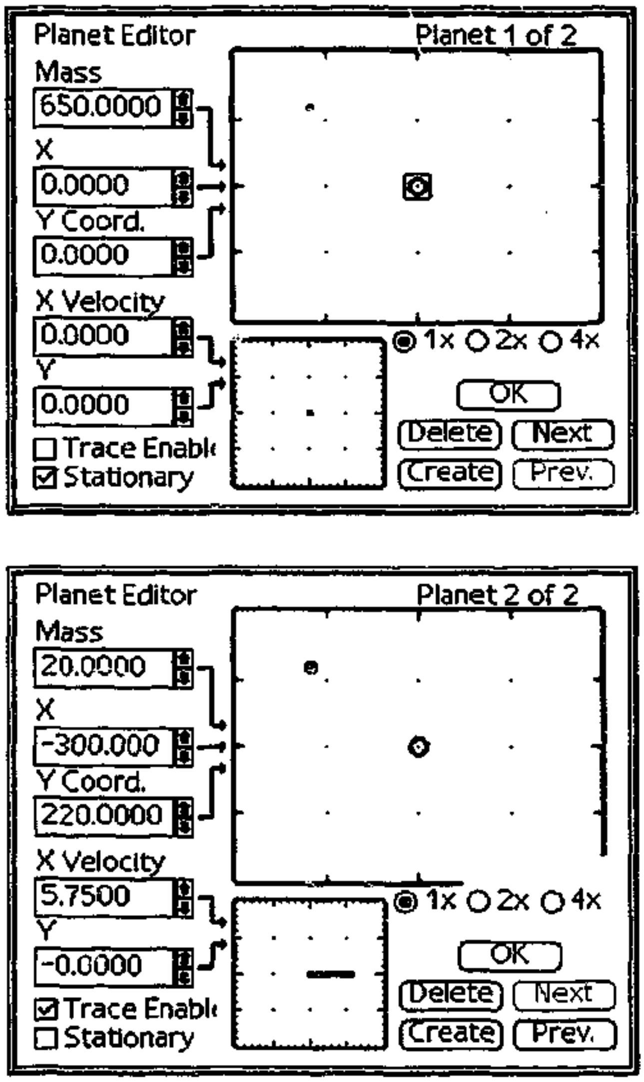


Figure A-14: Probe G-4 setup.

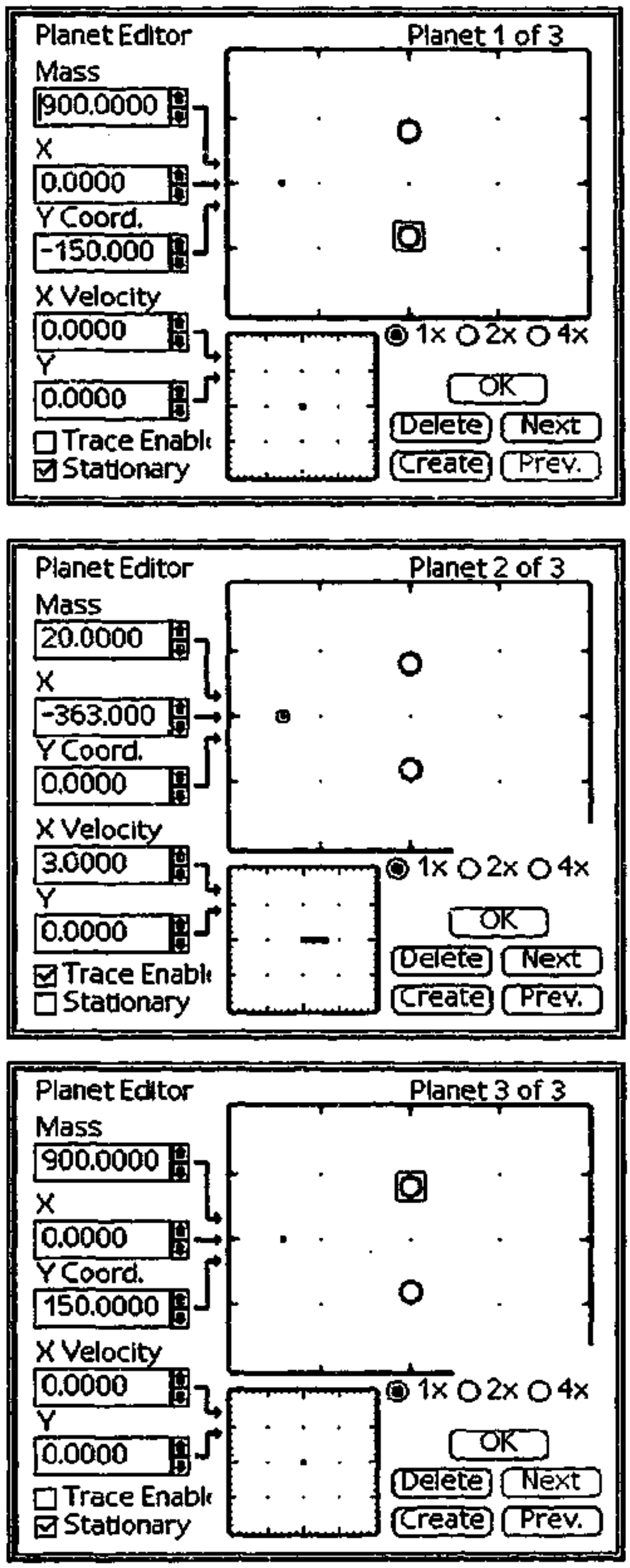


Figure A-15: Probe G-5 setup.

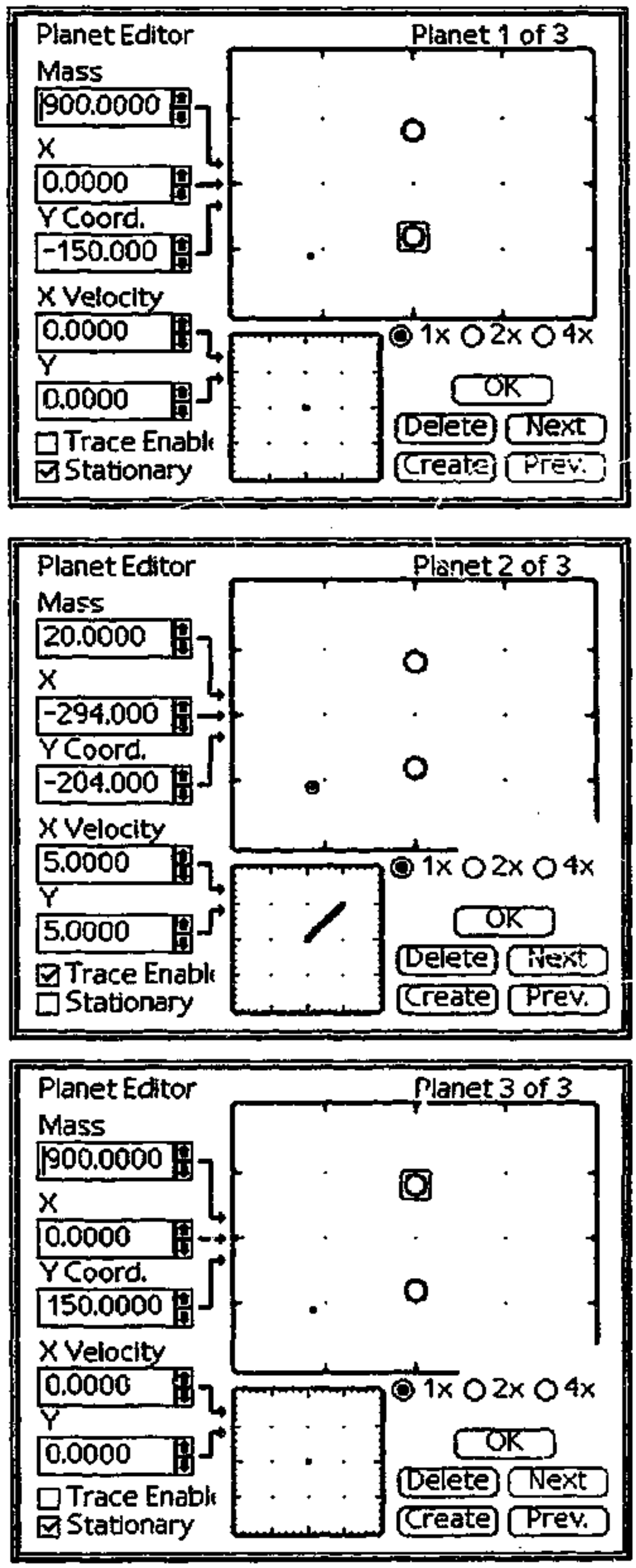


Figure A-16: Probe G-6 setup.

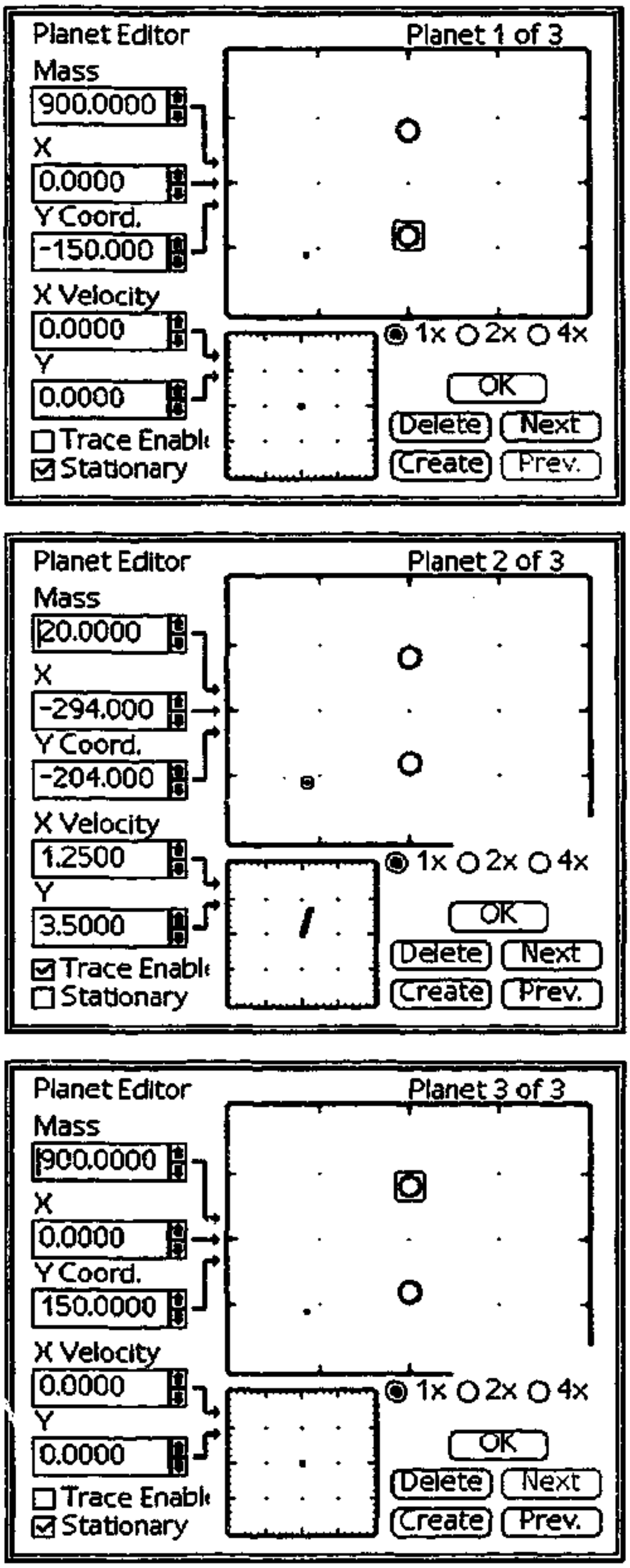


Figure A-17: Probe G-7 - main planet setup.

In this probe, all of the asteroids (numbered 2 to 17) have the same mass, initial velocity and Y-coordinate. Asteroids 2 through 17 are spaced 10 units apart along the x-axis, commencing from the initial position of planet 2.

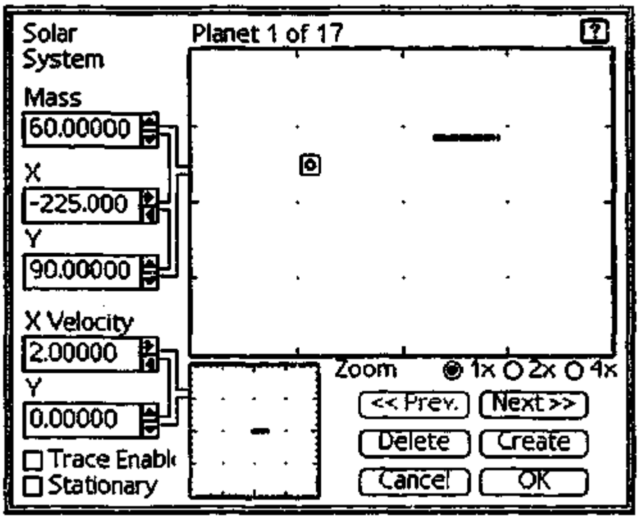


Figure A-18: Probe G-7 - typical asteroid setup.

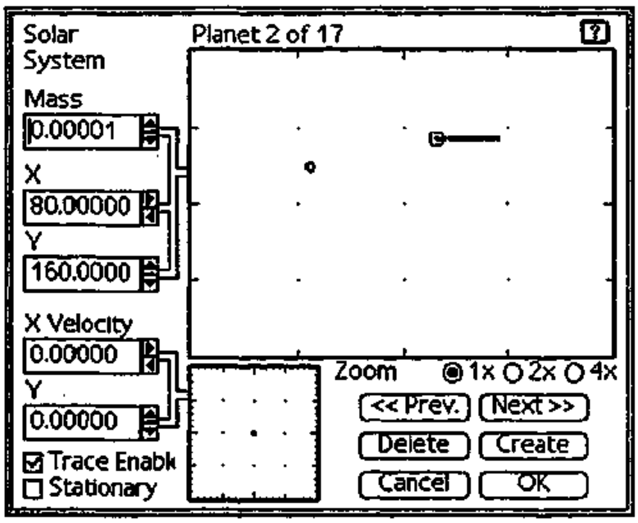


Figure A-19: Probe G-8 setup - typical 'grouped' planet. In this probe, all of the planets, except planet 12, have the same mass, initial velocity and Y-coordinate. The smaller planets are spaced 10 units apart along the x-axis, symmetrically around the initial position of planet 1.

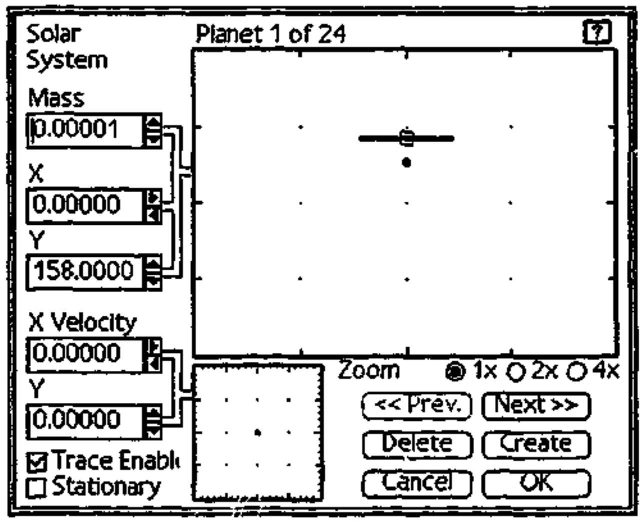


Figure A-20: Probe G-8 setup - single planet.

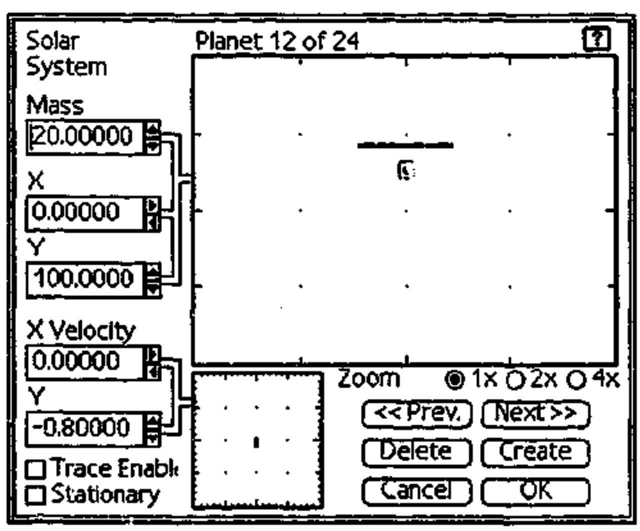


Figure A-21: demonstration of different asteroid orbits with identical mass and velocity.

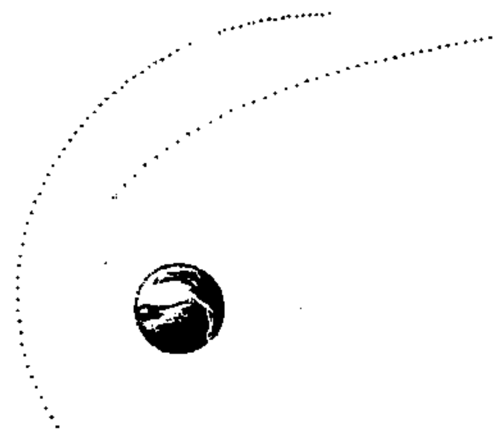


Figure A-22: Probe G-9 setup.

In this probe, all of the particles except planet 1 have the same mass, initial velocity and Y-coordinate. The smaller planets are spaced 7 units apart along the x-axis, from the initial position of planet 1.

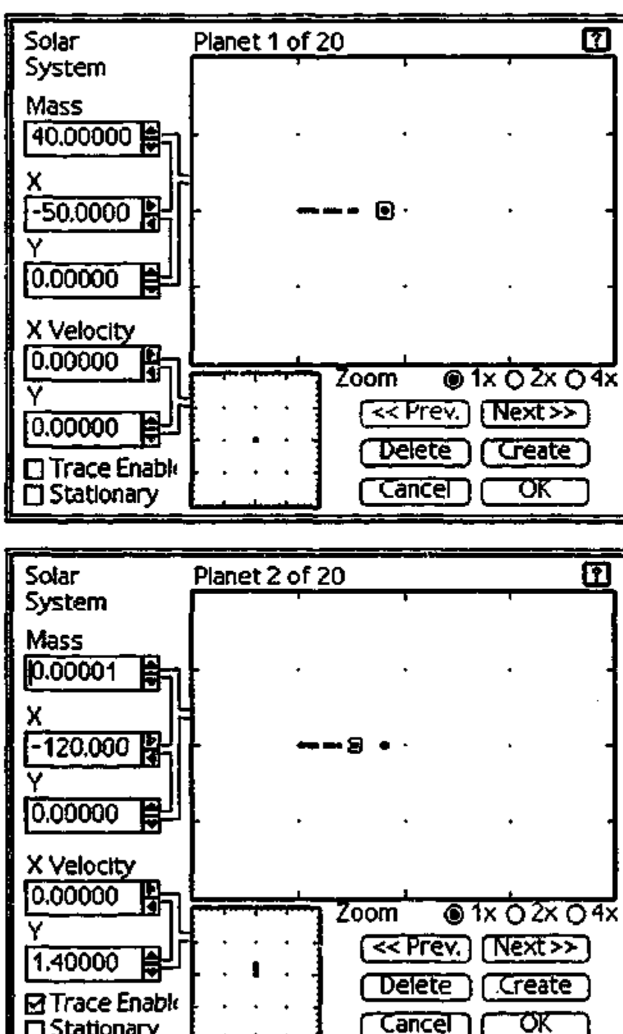
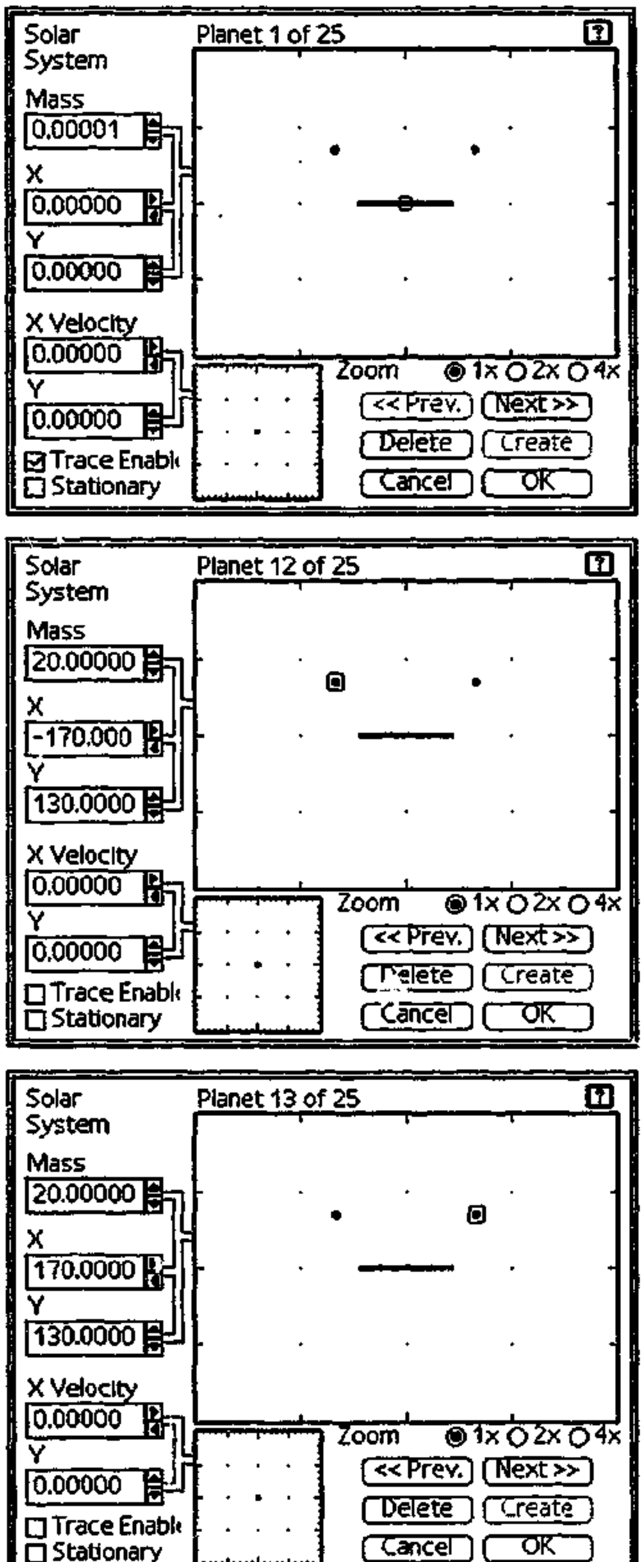


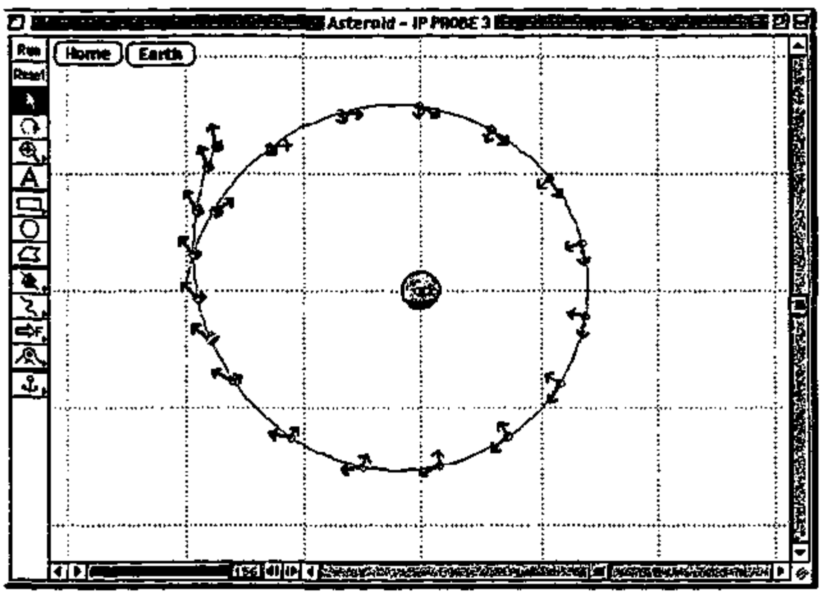
Figure A-23: Probe G-10 setup.



A.4.5 Interactive Physics™ probes

Figure A-24 shows the motion, and vector representation of gravity, used in the probes 1-4 of this series. Each probe presents the same motion, but displays different vectors to the observer. Participants can display other vectors by selecting them from a menu. A range of graphs can also be generated, showing a time-series of a particular vector quantity, as in Figure A-24, where velocity and 'total force' (the vector sum of all forces acting) are displayed. Probe5 is described in Chapter 6.

Figure A-24: Interactive Physics™ vector probe 3



A.5 Consent Form

MONASH UNIVERSITY ETHICS COMMITTEE
CONSENT FORM

Title Of Research Project: Teachers' Understanding of Gravity

---

1. INVESTIGATOR

I, Paul Stuart Nicholson, have fully explained the aims, risks and procedures of the research project to ....

Signed .... Date ....

---

2 THE PERSON GIVING CONSENT

I, ... (print name)
of ....(print address)
agree to take part in the research project described in the attached explanation, being conducted by Paul Nicholson, who has fully explained the research to me and given me a copy of the explanatory statement.
I understand that I am free to withdraw from the project at any time and have had the opportunity to have a member of my family or a friend present while the project was explained to me.

Signed ....Date ....

A.6 Plain language statement

Dear colleague,

My name is Paul Nicholson. I am a Ph.D. student in the Faculty of Education at Monash University. My research study, "Teachers' understanding of gravity", is being conducted as part of my Ph.D. program under the supervision of Associate Professor Anne McDougall. I would like to invite you to take part in this study.

Purpose of the study
The purpose of this study is to examine student teachers' thinking about how objects move under the influence of gravity.

Anticipated outcomes
The information collected in this study will be used to identify the understandings that science teachers have about motion under the influence of gravity, and will also lead to the development of design principles for creating better teaching software in physics education.

Methods and procedures
Should you agree to take part in this study, your total time commitment would be approximately 1.5 hours, which consists of a one-hour interview and, at a later time, approximately 30 minutes to verify a written transcript of the session.

- Before or during the interview you will be asked to complete a short questionnaire on your understanding of selected physics concepts,
- During the interview time you will be interviewed about your understanding of particular physics topics and contexts related to gravity. This interview will require you to watch some video clips, to use some computer software, and will be audio taped and videotaped. A written transcript of the session will be made from the tapes. This will be made available for your inspection should you so desire.

Participation
Your participation is entirely voluntary. You are free to withdraw from this study at any stage.

Confidentiality
All information collected in this study is in strictest confidence. The identity of all persons will remain anonymous and confidential. In all documents generated in this study you will be referred to by a coded alias.

Complaints
Should you have any complaints concerning the manner in which this research project is being conducted, please do not hesitate to inform the researchers in person or you may prefer to contact the Faculty of Education Ethics Committee or the University's Standing Committee on Ethics in Research in Humans.

Further Details
If there are any questions that you have with regard to this study, please feel free to contact me at:

Phone: (03) 9244-6922
Fax: (03) 9562-8808
E-mail: pauln@deakin.edu.au

Thank you for your assistance,
Paul Nicholson

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