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Strategies adopted by undergraduate physics students when modelling solutions to hands-on tasks

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Abstract

Over the last three to four decades there has been a focus on the role of models and modelling in physics education. At the same time, there has also been a move away from the use of recipe-style tasks in physics laboratories to inquiry-based problem solving. From the ensuing research, model-based views of physics have emerged which have contributed to the fields of pedagogy as well as epistemology; the contribution depending on whether the research interest has been that of education or philosophy of science. And while there is still some consensus seeking on the nature and definitions of modelling, there has in recent years been a shift to research questions that consider how models are constructed by students when engaged in hands-on tasks.

Model-based instruction courses have been researched at length, but there is a perceived gap in the research that considers the hands-on strategies that are actually employed by 1st-year university students who are in a teaching and learning environment in which the physics curriculum emphasises the modelling of real world systems. This study contributes to this research area in that it investigates the strategies students actually adopt when engaged in student-driven, hands-on laboratory tasks and interprets those strategies in terms of a particular model-based view of physics; a model-based view that posits that the processes of modelling are those of the *particularisation* and *application* of physics theory, the *idealisation* and *approximation* of real world phenomena, and the eventual *realisation* of a conceptual model.

In this interpretivist study, data were collected from a sample of 47 students by means of: a) videoed observations of small groups of two to four students as they engaged with the hands-on tasks, b) written responses on task-related worksheets, and c) selected, post-task individual interviews based on critical incidences during the modelling of the hands-on tasks. All of the observations and the interviews were transcribed and annotated and were analysed using a grounded theory approach.

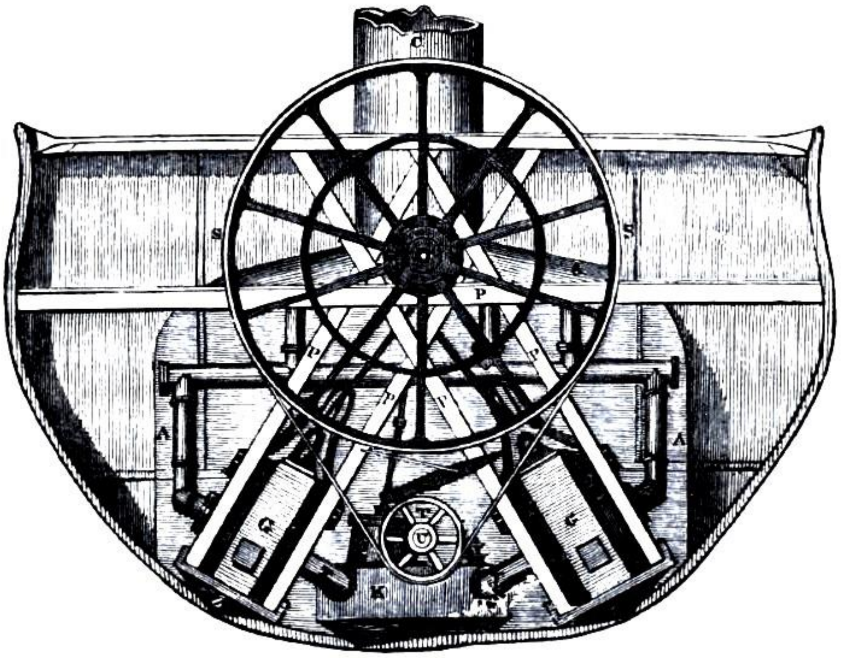
The findings show that students readily adopt strategies that employ the ‘epistemological resources’ they already have, i.e., they embrace *rule systems* and show skill in checking, repairing and refining the solutions they develop. They are proficient in adopting a formula-centred strategy to particularise and apply the requisite theory and to realise a suitable conceptual model, but this approach lends itself to the formulation of a ‘syntactic’ rather than a ‘semantic’ physical model. Moreover, students do not generally exhibit the commensurate level of skill in idealising and approximating the real world phenomena they are investigating. Students appear to use ‘indirect’ strategies when required to idealise and approximate real world phenomena. The findings also show that there is a discernible cyclic pattern in the way in which the groups of students develop the models that are solutions to given hands-on tasks. This cyclic pattern does not necessarily describe the engagement of any one student, but suggests that there is a particular order in the strategies the group employs, which supports the notion that there is an underlying distributed cognitive process in model-based reasoning when conducted within a group.

Research, by others, into the processes of modelling in model-based instruction have proposed various ways of supporting the teaching of modelling, but it is suggested these methods do not necessarily describe the way in which this student sample actually go about solving the given hands-on tasks. Based on the findings of this study, it is suggested that while modelling, and particularly the processes of idealisation and approximation, should be taught explicitly, these should not be done in a way that presents modelling as an exercise separate from the regular, lecture-based problem solving exercises. It is suggested that modelling should complement what has become known as traditional teaching of physics as this approach builds on the method of teaching and learning to which the students are accustomed.

Preface and acknowledgments

For 8 of the 30 odd years I spent in industry - in which I worked as a millwright, a marine automation technician and finally, for the bulk of the time, as an engineer - I worked on ships. During those years I developed an interest in one of the heroic episodes in marine engineering history, the design and building of the 19th century vessels the *Great Western*, the *Great Britain*, and the *Great Eastern*; the main fascination being the engineering insight of the architect of those early steamships, Isambard Kingdom Brunel (1806 – 1859). Brunel’s genius was expressed again and again in what can only describe as his having had a remarkable sense of what seemed right about a design; a special case in point being the engine-room layout of the first large propeller-driven ship, the *SS Great Britain*.

Fig. 1.



http://upload.wikimedia.org/wikipedia/commons/3/3b/SS_Great_Britain_transverse_section.jpg

Moreover, throughout my career, I have had the privilege of working with some remarkably talented technicians and engineers and it occurred to me that what made their contribution special was their ability to interpret their observations intuitively, often seeing things that I had missed. They seemed to have no difficulty estimating the suitability or otherwise of a part or a design, or the appropriateness of an adjustment. It seemed to me that these extraordinary people had something of whatever it was that made Brunel such a success and for many years I have wondered how they gained their engineering insight. At the same time I have wondered if the visualisation and observation skills they displayed could possibly be taught and learned.

Similarly there have been remarkable experimentalists who somehow knew what it was for which they had to look; those scientists who have been able to recognise some key effect in the melee of observable phenomena that made the difference between run-of-the-mill work and seminal findings. Once again, one has to wonder if it is possible to teach and learn whatever it is that makes this experimental difference?

The present work does not attempt to answer what it is that gives an engineer or a scientist that special ‘feel’ for successful design or experiment, but it does consider strategies taken by students of physics who are just starting out in their careers, possibly as experimentalists, and who may well be among those who develop the special skill that will make all the difference. In this sense, this study is something of a personal quest in that it considers a specific aspect of a much broader question to do with hands-on problem solving that has been on my mind for many years. Namely, how is it that some people are able to make sense of their observations so as to derive abstract, useful conclusions, while the same observations remain meaningless to others?

In this endeavour, I am deeply indebted to my supervisors, Andy Buffler and Fred Lubben, who have provided inspiration and guidance throughout this study; just as I am indebted to the Physics Department at the University of Cape Town and the students of the PHY1004W class of 2011. I have enjoyed their unwavering co-operation and assistance throughout.

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And finally, I wish thank my wife Jillian for the support and encouragement given to me over a number of years, she too is one of those special people who is able to see things without the need for someone to point them out.

Cape Town, 2014.

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1 Introduction

1.1 Modelling as an alternative to traditional physics curricula?

In the 1990 Millikan Lecture, Lillian McDermott suggested that an adequate outcome of an appropriate physics curriculum would be one which would provide that:

> a) students should have acquired a sound understanding of certain basic physical concepts, b) students should be able to describe the relationship between a concept and the formalism that is used to represent it, c) students should have developed sufficient proficiency in scientific reasoning (proportional, analogical, model-based, etc.) to apply the concepts and representations of physics, and d) students should be able to make explicit the correspondence between a concept or a representation and an actual object or event in the real world (McDermott, 1991, p. 303).

However, it has long been recognised that devising a physics curriculum that meets all these requirements has not been a simple task. For example, in an address to the Bartol Research Foundation of the Franklin Institute in 1950, W. F. G. Swann emphasised the importance of ideas in physics rather than facts. Swan stated that the study of physics comprised of two phases, knowledge of facts and knowledge of ideas, going on to suggest that "ideas are all important and that facts are necessary only to the extent sufficient to provide material for the manipulation of the ideas" (Swann, 1951, p. 182). Swann went on to suggest that teaching material that simply presented facts could be done away with and should be replaced by efforts devoted to teaching fundamental principles of physics. He went on to describe the tendency of some teachers of physics to systematise their courses to the point where, "Everything is neatly laid out and the student works hard and passes his tests frequently, alas, with very little comprehension of what he has been doing" (Swann, 1951, p. 185). Since then, Swan's view has been reflected in the results of physics education research through which it has been suggested that by using curricula in which "the student is not actively engaged in the process of abstraction and generalization" (McDermott, 1991, p. 304), the outcome has been inadequate in meeting the requirement for students to develop the necessary conceptual understanding of physics.

There is what has become known as a traditional way of teaching physics which is characterised by the way in which physics problems are presented to students. In this traditional way, the required observations, assumptions, idealisations and approximations relative to the problem are already fully formulated when the problem is presented to the students. The outcome of this teaching method is that little inductive reasoning is called for as the students are merely required to apply specific solutions to these problems (McDermott, 1991). This view appears to be reflected by that of Van Heuvelen (1991) who reported that physics students approach problem-solving with a limiting formula-centred strategy, while Halloun suggested that "(students) tend to view solving a physics problem mainly as a task for selecting mathematical formulae to relate variables in the problem" (Halloun, 1996, p. 1019-1020).

Although this shortcoming had been recognised, McDermott had suggested that drives at curriculum reform had by-and-large, to that date (1991), been "discouraging" (p. 302). Nevertheless, research in physics instruction had moved to an approach influenced by studies in cognitive psychology as well as the refinement of constructivist theory (McDermott, 1991, p. 305), a theory by which it was suggested that physics students needed to actively build conceptual understanding on the basis of their existing knowledge and that this 'meaning-making' or 'sense-making' needed to be guided by structured teaching interventions (Driver, 1983, p. 9). It had also been suggested that among other interventions, "students need to use concepts and skills repeatedly in a variety of contexts" (Van Heuvelen, 1991, p. 896).

As part of these efforts at curriculum renewal, organisations such as the American Association for the Advancement of Science (1990; 1993) and the National Research Council in the USA (1996) produced reports in which it was suggested that the explicit teaching of modelling should be adopted to correct the perceived deficiency in traditional physics teaching and learning. In making this recommendation the pedagogic expectation was that "by learning how to structure the content of physics theory around models, and how to solve problems by modelling, students will reach a meaningful understanding of physics which would resolve the perceived deficiencies" (Halloun, 1996, p. 1020). To this end, there has been a greater reliance on explanations based on the structure and language of modelling in the development of modern methods in science instruction (Etkina, Warren & Gentile, 2006). However, with the introduction of modelling as a method of instruction there had also arisen a range of interpretations of the word ‘model’ in the relevant literature which prompted the comment that there had grown a “forest of models” (Greca & Moreira, 2001, p. 110). In some cases, there has been a narrower interpretation of modelling as in the view that “the models in physics are mathematical models” (Hestenes, 1987, p. 441), while Clement writes, “I will refer to all relevant analogies, explanations, and theoretical models collectively as scientific models construed broadly” (Clement, 2009, p. 74). The focus on modelling has given rise to a body of model-related research in education in which there have been contributions to both the fields of epistemology and pedagogy (Matthews, 2007, p. 647). However, it has been suggested that “most authors in science education seem to develop their views on models rather independently from the philosophical underpinnings” (Koponen, 2007, p. 754).

Having recognised, for example, that in many traditional physics courses, “problem-solving techniques appear to students as a collection of weak methods that include hunting for formulas with familiar symbols in them, or matching to similar worked-out examples” (Chabay & Sherwood, 2004, p. 439) - the outcome of which is to confirm “in students’ minds the conviction that physics is a large number of disconnected formulas” (Chabay & Sherwood, 2006, p. 329) - Ruth Chabay and Bruce Sherwood have proposed a curriculum that provides for:

> Discussions of physical principles (that) involve the properties of real matter instead of focussing solely on idealized macroscopic, material-independent situations. (And) rather than emphasizing algebraic manipulation in sanitized exercises, the course can offer opportunities for students to explain and predict complex phenomena, reasoning from an atomic model of matter and a small number of fundamental principles. In this process students need to make approximations, to idealize complex systems, and to think through the consequences of a particular model – activities that are central to physics but absent from the traditional curriculum (Chabay & Sherwood, 1999, p. 1045).

1.2 The adoption of a model-based view of physics

With reference to Giere (1988), Brewe has suggested that “the value of models is clear to most practicing scientists (because) models are the basis for theoretical and experimental research which makes them the basis for knowledge development, reasoning, and problem solving” (Brewe, 2008, p. 1156) and that, “modelling is the establishment of semantic relations between theory and phenomena" (Greca & Moreira, 2000, p. 2). Moreover, it has been suggested that an understanding of the epistemology of model construction is necessary in order to ascertain which models "accurately reflect the world and its processes, and which models are conducive to genuine knowledge" (Matthews, 2007, p. 649), all of which is why the role of models and modelling has been widely adopted in the practice of physics.

In the efforts to develop an understanding of the role of models and modelling in physics, researchers have drawn from cognitive psychology research, an example being Greca and Moreira's (2001) research into the relationships among physical models, mathematical models, and mental models in the process of understanding and constructing physical theories; as well as from philosophy of science research, an example of which is Koponen's (2007) critical re-analysis of the Semantic View of Theories (SVT) and the philosophical underpinnings of models and modelling in physics education.

Along with the development of an understanding of models in the practice of physics, the pedagogical advantages of modelling have been recognised. From the initial work by researchers like Hestenes and Redish there has emerged the publication of work such as *Mediated Modeling in Science Education* by Halloun which, as the author suggests, "Outlines fundamental aspects of what we hope will evolve into a fully-fledged modelling theory of science education" (Halloun, 2007, p. 655). However, the adoption of modelling in teaching and learning appears not to have been straightforward because, as has been suggested by Brewe (2008), there are significant philosophical differences between traditional problem-solving and the application and adaptation of models. Unlike the traditional way of teaching physics, in which the topics are arranged in discrete textbook chapters, model-based instruction concentrates on a few general models that are continually revised and refined (Brewe, 2008).

Notwithstanding the difficulties encountered, over the last fifteen years numerous model-based curricula innovations have been underway (Nersessian, 2008), examples of which are *Matter & Interactions* by Chabay and Sherwood (1999), *Teaching physics with the Physics Suite* by Redish (2003) and *Investigative Science Learning Environment* (ISLE) by Etkina and Van Heuvelen (2007). And more recently, Zwickl, Finkelstein and

Lewandowski (2013) have proposed a framework for incorporating model-based inquiry into undergraduate physics laboratory courses and it is in this area that the present work makes a contribution.

1.3 The aim of the research

A detailed breakdown of the research questions is given in 2.1.7 after the definitions of the modelling processes referred to below have been presented.

For the purposes of the present work, it is posited that the modelling of solutions to hands-on tasks may be considered in terms of a particular model-based view of physics - one in which it is proposed that there are five processes in modelling, *viz.*: *particularising, applying, realising, idealising* and *approximating*. These five modelling processes are defined in 2.1.5 and 2.1.6 below and are listed here as they are relevant to the contextualising of the research questions.

As noted, over the last two decades there has been a considerable amount of research into the questions of models and modelling in physics, both from an epistemological as well as an educational point of view. At the same time, there has been a move away from recipe-style laboratory work to inquiry-based teaching and learning. Sunal (2004) has given a summary of the relevant supporting work by Barnes, Driver, Karplus, Erickson, Nussbaum and Novic, Renner, and Rowell and Dawson and there have been strides made in the implementation of the outcomes of this research by physics educationists such as Etkina and Van Heuvelen (2007), and more recently by Zwickl, Finkelstein and Lewandowski (2013). These developments have taken place against the backdrop of contributing advances in psychological research into cognition, Johnson-laird (1983); theory-ladenness, Brewer and Lambert (2001); epistemology, Hammer and Elby (2003); and strategies in problem solving, Klahr and Dunbar (1988) and Clement (2009), again, to mention only some of the noted researchers.

However, within this body of work, there is a gap in the research relevant to teaching and learning in laboratories, specifically in the use of hands-on tasks. The present work focusses on the strategies students actually adopt when they solve hands-on problems, with the view that the results of this research would contribute to the understanding of model-based instruction may best be implemented in laboratory work. In its justification, this research takes an approach similar to that by Kuo, Hull, Gupta and Elby (2012) – who considered mathematical reasoning in solving physics problems – in that the focus is on *how* the problem is actually solved; i.e., which strategies are actually used? It is of relevance that in this work consideration is given to the use of ‘epistemological resources’ that students may bring to bear in solving these problems (Hammer & Elby, 2003).

2 Literature Review

The literature review for the present work is presented in four sections which refer to: 1) a model-based view of physics, 2) models in teaching and learning, 3) the role of hands-on tasks in conceptual development, and 4) cognitive processes, theory-ladenness, student epistemologies, problem-solving and strategies.

2.1 A model-based view of physics

There has, over the last three to four decades, been a focus on the role of models and modelling in physics and physics education where it has been recognised that models are a "means for a more authentic education, facilitating a scientific way to describe, explain and predict the behaviour of the world and acquire knowledge" (Koponen, 2007, p. 766). From this body of research there has emerged what has been variously described as a 'model-based view of physics' although, as was reported by Grandy and Duschl, the word 'models' may include: mathematical models, physical models, analogical models, visual or pictorial models and computer models. Indeed, "Our taxonomy of models and their apparently disparate nature might lead readers to wonder if anything unites them other than the label" (Grandy & Duschl, 2007, p. 148).

The body of model-related research that has emerged has been broadly approached from two points of view, that of the philosophy of science, and that of classroom practice (Harrison & Treagust, 2000). These two approaches have been manifest in: a) the outcome in which the pedagogical approach is directed at having students construct models with comprehensible rules and then validating these models in 'matching' experiments; and b) the philosophical approach which has concerned itself with "the epistemological question of models in representing phenomena of the physical world and the relation of such models to theory" (Koponen, 2007, p. 754-755).

The epistemological view has been researched primarily through the approach of the philosophy of science by researchers such as Black (1962), Jammer (1974), Giere (1988 & 2004), Morrison and Morgan (1999), Nola (2004), Portides (2005 & 2007), Nersessian (2006 & 2008), Koponen (2007) and Besson (2010) to name a few. And the educational point of view has been investigated by researchers such as Hestenes (1987, 1992 & 2007), Redish (1996 & 2003), Van Driel and Verloop (2002), Halloun (1996 & 2007) and Greca and Moreira (2000 & 2001), once again, to mention only a few.

These two approaches are reflected in the suggestion by Van Driel and Verloop that in the enterprise of modelling, models may be classified according to their ontological status and “it is important to distinguish a *scientific consensus model* from a *curricular model*, that is, a simplified version of the former that is included in a formal curriculum (italics in the original)” (Van Driel & Verloop, 2002, p. 1257).

When considering a *scientific consensus model*, in the context of modelling in physics, the emphasis is on the philosophical underpinnings and epistemologies of modelling and in this regard it is of note that according to Portides, the understanding of the theory/experiment relationship is “a key meta-scientific ingredient in enhancing the ability to think scientifically” (Portides, 2007, p. 700). To this end, the model-based view of physics adopted for the present work has adopted “philosophical views currently in use within science education (that) are more or less related to the Semantic View of Theories (SVT) that originates from works by Suppes (1962), Suppe (1977), van Fraassen (1980) and Giere (1988)” (Koponen, 2007, p. 752).

Le Bihan (2012) summarises the three key claims underpinning the Semantic View of Theories as follows:

1) (Models) Scientific theories and scientific practice can be studied through the scientific models that scientists typically use to represent the world;
2) (Scientific=Logical) Scientific models can be construed as logical models;
3) (Adequacy) Studying scientific theories by studying their models and construing scientific models as logical models provides the means to give an adequate account of what scientists typically use to represent the world in actual practice (Le Bihan, 2012, p. 250).

However, within the body of work that describes the Semantic View there are different interpretations as well as criticisms. For example, Le Bihan (2012) has argued that the criticisms have centred on the whether a strong (rigorous) interpretation, or not, should be made of the three claims made by the Semantic View. If a strong interpretation of each of the three claims is made, then the criticism holds and the Semantic View fails, but if one does not commit to a strong interpretation of the three claims, then a "Modest Semantic View" is not only tenable, but is also a fruitful tool for the philosophy of science (p. 251).

Giere (2004) appears to take a more pragmatic approach when considering how models are used to represent reality by using the example that the syntax and the semantics of language "only become visible, so to speak, in the study of written language", and so the study of models should begin with the way in which scientists use models (p. 743). Giere suggests that a study of modelling should focus on *representation*, which he describes as "a two-place relationship between linguistic entities and the world", which he explains in terms of the statement:

> *S* uses *X* to represent *W* for purposes *P*. Here S can be an individual scientist, a science group, or a larger scientific community. *W* is an aspect of the real world. So, more informally, the relationship to be investigated has the form: Scientists use *X* to represent some aspect *W* of the world for specific purposes. The question is, "What are the values of the variable *X*?" Focussing on scientific practice, one quickly realises that *X* can be many things, for example, words, equations, diagrams, graphs, photographs, and increasingly, computer-generated images (Giere, 2004, p. 743).

Given that there are a number of interpretations and approaches to the study of modelling, the underpinnings of the adopted model-based view of physics used in this study have been taken from the work by Jammer (1974), Morrison and Morgan (1999), and Greca and Moreira (2001); and the approach to this view is described in the following sections.

2.1.1 A philosophical underpinning for the adopted model-based view of physics

It had been suggested by Jammer (1974) that the interpretation of a physics theory may be done via the so-called *partial interpretation thesis*. By this explanation, a physical theory *T* may be seen as having at least two components, namely: the abstract formalism *F* of the theory and a set *R* of the associated rules of correspondence. The formalism *F*,

> is a deductive, usually axiomatised calculus devoid of any meaning; it contains, apart from logical constants and mathematical expressions, non-logical (descriptive) terms like "particle"

> and "state function," which *ibid*. are generally highly suggestive of physical significance, (but) the terms have no meaning other than that resulting from the place they occupy in the texture of *F* (Jammer, 1974, p. 10).

To transform the formalism *F* into a deductive system of statements which make the formalism physically meaningful, the appropriate non-logical terms and/or some of the formulae in which they occur have to be correlated with observable real world phenomena. "These correlations are expressed by the rules of correspondence *R* or, as they are sometimes called, coordinating definitions, operative definitions, semantic rules, or epistemic correlations" (Jammer, 1974, p. 10).

Jammer denotes the formalism *F*, when that formalism has been partially interpreted by the set of correspondence rules *R*, as F_R, while, when *F* is partially interpreted by a different set of correspondence rules *R'*, the formalism thus partially interpreted is denoted by $F_{R'}$ (p. 10-11). In this way the same formalism *F* may be partially interpreted by different sets of correspondence rules in a number of ways. Jammer goes on to propose that "the value of a scientific theory is not gauged by the faithfulness of its representation of a given class of known empirical laws, but rather by its predictive power of discovering as yet unknown facts" and in order to do so, the partially interpreted formalism, F_R "has to be supplemented by some unifying principle which establishes an internal coherence among the descriptive features of the theory and endows it thereby with explanatory and predictive power." This 'unifying principle' is implemented by "the construction of a "picture" or a model *M* for the theory *T*, a process which is also often referred to as an interpretation of the theory". Jammer suggests that the model *M* is "often defined as a fully interpreted system", and while the logical structure of the model *M* may be similar to that of the partially interpreted formalism F_R, its "epistemological structure differs significantly from F_R." and thus the model *M*, "becomes instrumental in strengthening the predictive power of the theory *T*" (Jammer, 1974, p. 11-12).

Similarly, and in regard to the characterisation of scientific theory, Morrison and Morgan (1999) have suggested two views have been taken: 1) the syntactic view in which the 'scientific theory consists of an axiomatisation in first-order logic' and in which the theory is expressed in terms of its logical form along with correspondence rules (additional sets of definitions) that provide meaning, i.e., the semantic content, or 2) the semantic view in which the theory is presented by “identifying a class of structures as its models”; with the difference being that “it is the models (rather than the correspondence rules) that provide the interpretation of (the theory)” (Morrison & Morgan, 1999, p. 2-3).

According to Morison and Morgan, the semantic view (of the interpretation of physical theories) has as its focus what are referred to as ‘physical models’. The “physical model is taken to represent, in some way, the behaviour and structure of the physical system; that is, the model is similar to what it models” (Morrison & Morgan, 1999, p. 5).

> Physical models can be constructed in a variety of ways; some may be visualisable, either in terms of their mathematical structure or by virtue of their descriptive detail. In all cases they are thought to be integral components of the theories; they suggest hypotheses, aid in the construction of theories and are a source of both explanatory and predictive power (Morrison & Morgan, 1999, p. 5-6).

Morrison and Morgan (1999) go on to suggest that models occupy an autonomous role in science in that they are partially independent of both theories and the world and so can be used as instruments of exploration in both domains. In their structure, in which models include some of both theory and the real world in their functionality, models are autonomous in that they can function as a tool or an instrument that is independent of the ‘thing’ on which it operates. As such, models “mediate between things; and like tools, can often be used for many different tasks”. Models represent either some aspect of theory or some aspect of the world, or both at once, and the significant role of a model in science is that while we may not learn much from using a model, “we learn a great deal from building the model and manipulating it” (Morrison & Morgan, 1999, p. 10-12). In this way, models have epistemic value in that “models are both a means to and a source of knowledge” (p. 35).

In considering the same topic, Greca and Moreira (2001) have suggested that:

> The physical models constitute the semantic structure of a physical theory and determine the way the classes of phenomena linked to them should be ‘perceived’. *ibid.* (However), the semantic content of a physical theory is not referred to systems, objects, or events perceived through direct observation: the relationship between theory and reality is always mediated by some physical model. *When the statements of the theory are concerned with a simplified and idealised physical system or phenomenon, the resulting description is a physical model* (italics in the original) (Greca & Moreira, 2001, p. 107).

In summary of this section then, as pointed out Griere (1988), the general (syntactic) laws of physics, such as Newton's laws of motion and the Schroedinger equation, are not really statements about the world. They are only a part of the characterization of theoretical models which in turn may represent various real systems.

> There is no real system for which the basic form of the Schrodinger equation by itself describes a model, no more than $F = ma$, by itself, defines a model of anything. One always needs more details (the semantics), specific force functions, approximations, boundary conditions, and so on. Only then does one have a model that can be compared with a real system (Giere, 1988, p. 90).

2.1.2 Physical and mathematical models

Drawing from the philosophical underpinnings outlined above, Greca and Moreira have suggested that the ‘physical model’ develops, fully, the potentiality of the theory and through these physical models the simplifications, the linkages, and the necessary constraints or the internal structures of phenomena are captured, even if they are not directly observed. The physical models therefore “constitute powerful heuristic “pictures” which in themselves sum up the essential aspects of the theory so that it is possible to “visualise” with more ease, through them, the explanatory principles of the theory” (Greca & Moreira, 2001, p. 108).

It has been noted by Greca and Moreira that although those authors refer to physical models as “pictures’ and “visualisations”, these terms should not be understood in the narrow sense of what is observed visually. Because the relationship between the physical model and the real world phenomena that it may represent is expected to be complex, the descriptions of pictures and visualisation “should be understood in their broad sense, and not as a pictorial relationship in which each element of the model corresponds to an element in reality" (Greca & Moreira, 2001, p. 108).

According to Greca and Moreira, mathematical signs represent the formalism of the theory; they are its set of statements without their semantic content. The mathematical symbols represent the syntactic structure of the theory and these statements may be expressed in terms of equations in a 'mathematical model' that constitutes a deductively articulated axiomatic system. The authors stress the point that the semantic interpretation of whatever system is being interpreted should initially be done through a physical model, and only thereafter can the values of the variables obtained through the use of mathematical equations be identified with the magnitude properties of the system. Greca and Moreira go on to suggest that while it may be that some physicists consider that they 'see' the problems in terms of the mathematical equations, "it is common to accept that comprehension in a particular field of physics is attained when it is possible to predict a physical phenomenon from its physical models, without having to refer to the mathematical formalism" (Greca & Moreira, 2001, p. 108); with the caveat that this statement may not be true for more advanced fields of physics in which the interrelationships between the physical and mathematical models is much more complex.

The authors end this section of their 2001 paper, with the statement that "*the understanding of a scientific theory would require the constructions of mental models of its physical models in the mind of the one who wants to understand* (the theory) (italics in the original)" (Greca & Moreira, 2001, p. 108).

2.1.3 Mental models

Mental models are discussed in 2.5.1.1 below, but are introduced here since a clear distinction needs to be made between what is meant by a physical model and a mental model. In defining mental models it is necessary firstly to draw the distinction between *external* and *internal* models. External models are held in the public domain in "distributed cognitive systems" (Nersessian, 2006, p. 701), as is the case with mathematical and physical models that are ultimately reproduced in texts, as opposed to internal models, more commonly known as mental models, which are held idiosyncratically in the mind of an individual (Johnson-Laird, 1983; Redish, 2003; Hestenes, 2006).

A mental model is an internally held "structural, behavioural, or functional analog representation of a real world or imaginary situation, event or process. It is an analog in that it preserves constraints in what it represents" (Nersessian, 2008, p. 93). The role of the mental model is "to account for the individual's reasoning both when they try to understand discourse and when they try to explain or predict the physical world behaviour" (Greca & Moreira, 2001, p. 108).

2.1.4 Conceptual models

Gobert and Buckley have defined 'expressed' models as 'conceptual' models (Gobert & Buckley, 2000, p. 892) and according to Greca and Moreira, a conceptual model is "an external representation created by researchers, teachers, engineers, etc., that facilitates the comprehension or the teaching of systems or states of affairs of the world." Furthermore, "conceptual models are precise and complete representations that are coherent with scientifically accepted knowledge" and "these external representations can materialise as mathematical formulations, analogies, or as material artefacts" (Greca & Moriera, 2000, p. 5).

2.1.5 A particular model-based view of physics

Given that the theories of physics are abstract formulations that have been produced and accepted by the community of physicists (Buffler *et al.*, 2008, p. 431), and given that these theories may be represented by a partially interpreted formalism *F* and a set of correspondence rules *R*, and given that this partial interpretation of the theory may be fully interpreted by the construction of a physical model in which the behaviour and structure of a physical system are incorporated, then there must be means to introduce a coherence that endows the physical model with explanatory and predictive power (Jammer, 1974), i.e., there

> must exist a methodology of match-making between theory and experiment, but in order to make the correspondence between theory and real world phenomena, both the theoretical

> prediction and the experimental result needs to be structured in a mutually compatible form (Buffler, Pillay, Lubben and Fearick, 2008, p. 431).

A framework for this match-making has been proposed in a model-based view of physics by Buffler, Pillay, Lubben and Fearick (2008) and is depicted in Figure 1.

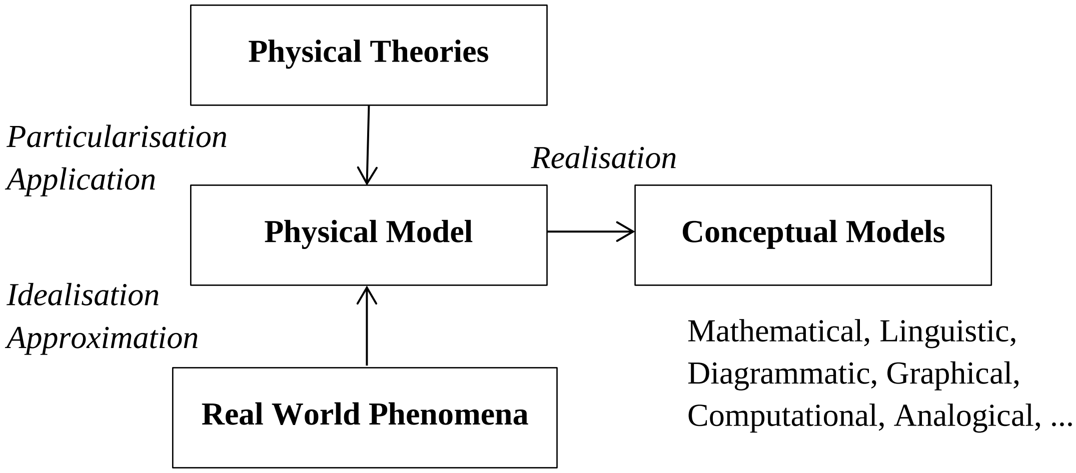

Figure 1: A model-based view of physics by Buffler *et al.* (2008)

Within this interpretive framework, it has been proposed that there are five distinct modelling processes that are instrumental in the interpretation of physical theories as they are matched to real world phenomena, and these five modelling processes culminate in the expression of the physical model so formed, as a conceptual model.

2.1.6 Modelling processes within this model-based view of physics

The five identified modelling processes, as have been depicted in Figure 1, have, for the purposes of the present work, been defined as follows:

1) ***Particularisation***: The process to name specially, to itemise or to state in detail, the statements (mathematical expressions, logical constants and non-logical terms; as well as the co-ordinating and operational definitions, semantic rules and epistemic correlations) of a scientific theory (Greca & Moreira, 2001).

2) ***Application***: The process of applying a particularised scientific theory for use in a specific case or for a practical purpose, as in the application to solve a posed problem in physics.
3) ***Realisation***: The process to conceive as real, to convert into actuality or to bring the modelled solution into concrete existence, i.e., it is the production of the didactical version of the physical model in the form of a conceptual model (Greca & Moreira, 2001).
4) ***Idealisation***: The process to abstract - in the sense of choosing or taking away those features considered relevant and by implication ignoring features considered irrelevant - as well as the possible distortion of the descriptions of those features (Nola, 2004).
5) ***Approximation***: The process to approach what may be thought of as a ‘correct’ estimate, concept, or a given quantity or quality. It is to simplify the description of the observed physical system in order to give a description that is not exact, but is tractable and considered ‘close enough’ to the real-world phenomenon in question (Portides, 2007).

2.1.7 The detailed research questions

Following on from the introduction to the aim of the reseach given in 1.3, and with the definitions above, the following research questions were investigated:

1) what strategies do students adopt when required to *particularise* and *apply* physics theory and why do they adopt those strategies?
2) what strategies do students adopt when required to *realise* a physical model as a conceptual model?
3) what strategies do students adopt when required to *idealise* and *approximate* observations they have made of real world phenomena and why do they adopt these strategies?

2.1.8 Modelling the real world

Having considered a basis for drawing aspects of physics theory into a physical model, it is necessary to do the same for drawing aspects of real world phenomena into the model. The following sections consider the nature of idealisation and approximation for that purpose.

2.1.8.1 The roles of reasoning and experience in idealisation

In *Pendula, Models, Constructivism and Reality,* Robert Nola (2004) argues that idealized models are largely the products of our reasoning rather than our experience and he does so by referring to examples in which reason has had to overcome experience in order to produce a viable physical model. Nola draws on the work of Koyré, Feyerabend and Nowak, all of whom use the celebrated case of Galileo's astronomical observations and the Galileo-Newton development of the concepts of momentum; particularly the phenomena of the motion of the earth around the sun and free-fall. Indeed, Nola builds on a concluding paragraph in Nowak's *Remarks on the Nature of Galileo's Methodological Revolution* after noting that it is a useful characterisation of Galileo-Newton methodological breakthrough (Nola, 2004, p. 350):

> The Galilean revolution consisted in making evident the misleading nature of the world image which senses produce. We only see phenomena which are the joint effect of all the relevant influences. As a result, senses do not contribute in the slightest to the understanding of the facts. In order to understand phenomena the work of reason is necessary, (reasoning) which selects some features of the objects through idealisation and in their idealised models recognises some other features of the empirical originals. These models differ a great deal from their sensory prototypes, what is more, they present images of hidden relationships which could not be grasped with the aid of experience at all. Science idealising phenomena opposes common sense… (Nowak, 1994, p. 123).

In the 2004 paper, Nola discusses two aspects of Nowak's remark (above). The first is that, because our senses can be misleading, we may not always be able to perceive the hidden causes of what we actually observe, and the second aspect has to do with how "idealisations are to be made in science, even when the idealisations and/or their consequences run contrary to common sense and (to) what we in fact experience" (Nola, 2004, p. 350). The key assertion by Nola is that in the construction of models, idealising assumptions have to be made which render the model no longer 'strictly true', noting that:

> the model leaves out other features that one might envisage holding of real world systems, but which are inessential to the (phenomena) being modelled. The distinction between the essential and inessential, or primary versus secondary, features of models is an important aspect of Galileo's scientific method. Making this distinction is not one that can be based in experience but must be determined by reasoning, in the light of theory, about the model being constructed (p. 355).

Among Nola's examples is our reasoning that the earth goes around the sun while in our daily sensory observation and discussion, we refer to the sun as rising and setting, underscoring Nola's suggestion that, depending on the degree of idealisation of some given real world phenomenon, the resulting model that could satisfactorily explain the phenomenon in question may well be at variance with experience. Of note is that Nola does not suggest that reason always trumps experience, going on to make the point that there is "a complex dialectic between the two (i.e., between our reasoning and experience), in which neither dominates the other" (p. 353).

Nola suggests that once these reason-driven idealisations have been made the model may be tested by observation and experience to determine the extent to which they explain real world systems, in the full knowledge that the devised model may only fit the observed facts approximately (Nola, 2004, p. 355).

2.1.8.2 Note on the use of the notions of idealisation and abstraction

In some of the literature referred to in the present work, a distinction has been made between the words 'idealisation' and 'abstraction' and as such the distinction is recognised. For example, Portides (2005) suggests that abstraction, in the Aristotelian sense of 'taking away' or 'subtracting', is

> more than the notion of idealisation and as such captures a broader spectrum of thought processes involved in scientific action. *ibid*. Abstractions as genuine subtractions may also imply distortions of the features of the concrete system. However, distortions are only a very special kind of subtraction of features. These thoughts lead to the conclusion that idealisation is a special form of abstraction; and not the converse (Portides, 2005, p. 70-71).

However, for the purposes of this study, these terms are considered synonymous as the distinction is not considered relevant to the present work; unlike the distinction between idealisation and approximation, which is considered relevant.

2.1.8.3 Idealisation and approximation more fully defined

Leading on from the definitions given above, the definitions as adopted for the present work are expanded as follows:

1) ***Idealisation***: The process to abstract - in the sense of choosing or taking away those features considered relevant to the model and by implication ignoring features considered irrelevant - as well as possibly to distort the descriptions of those features. Abstractions (idealisations) may be formed by reducing the information content of a concept or an observable phenomenon, typically to retain only information which is relevant for a particular purpose. By this definition, it may be recognised that an object has a certain property, *P*, but we may ignore that property for the purposes of the model in question, or we may idealise in a strict sense in that, "we do not merely ignore that property; we regard *P* as a property that the object definitely does not possess" (Nola, 2004, p. 357).

2) ***Approximation***: The process to approach a correct estimate, concept, or a given quantity or quality. It is to simplify the description of the whole physical system in order to give another description that is not exact, but is tractable and close enough to the real-world phenomenon in question. Approximation also simplifies parts of the descriptions of individual features and properties of the physical system to that end (Portides, 2007, p. 705).

According to Nola, the reason for constructing (scientific) models is two-fold: firstly it is to construct the idealised model; and then to make inferences, from the idealised model so constructed, about "possible observations that might only fit our experience to some degree of approximation" (Nola, 2004, p. 350). If this is accepted to be correct then it may be expected that there could, on occasion, be a divergence between theoretical predictions and experimental data that has to be dealt with by some common-sense notion of 'approximation' (Portides, 2007, p. 699)[1]. In this way, there is a sense that together, through interplay, the two notions of idealisation and approximation "operate together in the construction of scientific models that aim to bring theory closer to actual physical systems" (Portides, 2007, p. 702).

2.1.8.4 Two approaches to approximating theory to the real world

Suárez (1999) has suggested that broadly speaking, there are two approaches to approximating theory to the real world. There is the 'approximation of the theory to the problem situation', which is brought about by changing or refining the theoretical expression so that it more closely represents the real world situation. The other is the 'approximation of the problem situation to the theory', where "simplifications (are made) of the problem situation itself" (Suarez, 1999, p. 174). The former method is known as '*construct idealisation*' while the latter '*causal idealisation*'.

In discussing the question of the limits of models, which also touches on questions of construct and causal idealisation, Morrison (1999) makes the distinction between the 'mathematical context' and 'models', pointing out that solutions to physics problems are expressed via a (mathematical) system of equations whose particular solutions refer to some physically possible coordination of variables and as with the case discussed by Suárez above, an approximation can be seen in two different senses. For example, when considering differential equations, there can either be an approximation so that there are approximate solutions to exact equations, as in say the case of $\mathrm{d}y/\mathrm{d}x - \lambda y = 0$ where the solution may be expanded as a perturbation series in λ. Alternatively there may be an approximation that delivers an exact solution to approximated equations.

In this regard, the

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[1] It is of interest to note that while the epistemic difficulties created by the notion of 'approximate' have been minimised in science through the application of statistical methods in the development of uncertainty analysis, approximation still represents a problem in the notion of truth, i.e., "If theoretical proposition X is 'approximately true' of observation Y, then strictly speaking, X is false" (Portides, 2007, p. 703), however, this is not a matter relevant to this study.

> approximation involves simplifying, in both a mathematical and a physical sense, the equations governing a theory before solutions are attempted; that is, one is concerned with solutions to a simplified theory rather than approximate solutions to an exact theory. In that sense every model involves some degree of approximation in virtue of its simplicity, but not every approximation functions as a model (Morrison, 1999, p. 42).

In the context of the present work, it is considered that the notion of *construct idealisation* falls within the ambit of particularisation while *causal idealisation* falls within the ambit of idealisation and/or approximation as defined herein; even though it is recognised that the mapping is not entirely one-to-one. Further, in the present work the ‘mathematical context’ referred to by Morrison is considered to be part of the physical model; and that within every physical model there is an implied mathematical model.

2.2 Models in teaching and learning

Having considered models and modelling from an epistemic point of view, i.e., from what Van Driel and Verloop (2002) would refer to as a ‘*scientific consensus mode*l’, it is necessary now to consider models and modelling from a more pragmatic classroom practice point of view, i.e., from the view of what has been described as a ‘*curricular model*’ (p. 1257).

Morrison and Morgan have proposed that “modelling allows for the possibility of learning at two points in the process. The first is in constructing the model, *ibid.* (and) the second is in using the model.” In this regard, “the model functions as an epistemic resource; we must first understand what we can demonstrate in the model before we can ask questions about the real (physical) system” of which the model functions as a ‘representative’ rather than a ‘representation’ (Morrison & Morgan, 1999, p. 31-33).

Further, it has been suggested by Buffler *et al.* that there are particular pedagogical advantages in the view that the process of physics problem-solving occurs at the level of the physical model (Buffler *et al.*, 2008, p. 432). Moreover, according to Greca and Moreira, in order for students to understand the conceptual models that have been used to present the physics theories to them, students should be taught, explicitly, to construct the physical models, and *perforce* their mental models, upon which the physical models have been based. However, (as at the time of publication, 2000), the "modelling processes through which it would be possible to facilitate the construction of these (requisite) mental models has not been explicitly emphasised" (Greca & Moreira, 2000, p. 8-9). It has been suggested by Greca and Moreira that

> in order to understand a phenomenon or a process in physics (the first step) is to construct mental models that will allow the individual to understand the statements that compose the semantic structure of the theory, being necessary, at the same time, to modify the way of perceiving the phenomena by constructing mental models that will permit him (her) to evaluate as true or false the descriptions the theory makes of them. When this double process is attained concerning a particular phenomenon, in such a way that the "results" of the constructed mental models (predictions and explanations) match those scientifically accepted, one can say that the individual has constructed an adequate mental model of the physical model of the theory (Greca & Moreira, 2001, p. 106).

However, it is also noted, as a complication in teaching and learning physics through model-based instruction, that when the conceptual models that may have been created as a result of this process are presented, there is no mention of the mental models "which had served as intermediate analysis levels to the comprehension of the physical phenomenon in question". Moreover, it is not necessarily true that there is a direct and simple relation between the conceptual model that may have been realised and the mental models that underpin them (Greca & Moreira, 2000, p. 6).

2.2.1 Modelling Instruction

According to Jackson, Dukerich and Hestenes, "The name *Modelling Instruction* (as applied to physics teaching) expresses an emphasis on the construction and the application of conceptual models of physical phenomena as a central aspect of learning and doing science" (Jackson *et al*., 2008, p. 10). The essence of Modelling Instruction is that the course content is organised around "scientific models as coherent units of structured knowledge; to engage students collaboratively in making and using models to describe, explain, predict, design and control physical phenomena" (Jackson *et al*., 2008, p. 11). This approach, as noted by Brewe, does not emphasise the solving of well-defined physics problems which have specific numerical answers (as is characteristic of traditional physics teaching), but, by contrast, “students in Modelling Instruction courses need to view correct model development as a goal” (Brewe, 2008). And even though the use of Modelling Instruction in university courses presents a challenge as far as the grading of the work is concerned, there is always a return to the point that “Modelling Instruction is a pedagogical approach that focusses initially on the qualitative aspects of model development and thereafter on the quantitative aspects of the model” (Brewe, 2008, p. 1159).

In the development of Modelling Instruction and related instructional material, a range of curricula have been developed that either refer explicitly to Modelling Instruction, e.g., Halloun & Hestenes (1987) and Brewe (2008); or are variations of the theme that generally adhere to the essence of Modelling Instruction as described above, but using differences or variants of description and terminology, e.g., *Matter & Interactions* by Chabay and Sherwood, *Teaching physics with the Physics Suite* by Redish, *Investigative Science Learning Environment* (ISLE) by Etkina and Van Heuvelen, *Spiral Physics* by D’ Alessandris. In each case the educators have produced a detailed model-based curriculum or, as has been suggested by Brewe, a curriculum that could be adapted for use in Modelling Instruction (Brewe, 2008, p. 1155).

2.2.2 Various interpretations within modelling and model-based instruction

As has been noted, while the principles and objectives of model-based instruction have been generally accepted, there has been a wide interpretation of the words used to describe models and modelling. For instance, in an *Introduction to model-based teaching and learning in science education*, Gobert and Buckley made specific reference to a ‘teaching model’ which was “used by teachers and curriculum writers” (Gobert & Buckley, 2000, p. 892); while, as previously noted, Redish suggested that a mental model has “to do with the existence, properties and interaction of objects” and therefore was a ‘physical model’; but in so-doing, Redish acknowledged that this view of the ‘physical model’ “may or may not agree with our current community consensus view of physics” (Redish, 2003, p. 24). Hestenes for example, does not refer to a physical model as defined in the present work, but does acknowledge a mental model as being related to “real things and processes” (Hestenes, 2006, p. 10).

There have also been differences in the way in which nomenclature and definitions from other disciplines has been applied to modelling, for example, in making the distinction between the internal and the external ‘worlds’ of modelling, Halloun used the terms *schemata* and *constructs* where: 1) *Schemata* are internal mental models that are tacit, idiosyncratic mental structures that cannot be explored directly and 2) *Constructs* are external models that are conceptual structures used to communicate explicitly with others. “Constructs may be equations, drawings, explanations, etc., that allow for the formation of common understanding of concepts, laws and hypotheses” (Halloun, 1998, p. 241). Furthermore, it was suggested that *schema* are more fundamental than *constructs* because they are the basis for the construct (Halloun, 1998). In this regard, and using the same terminology, Redish has taken the view that “the key to understand student reasoning is understanding the patterns of association that activate knowledge elements” where the ‘patterns of association of knowledge elements’ form the ‘knowledge structures’. When these knowledge structures are “activated together with high probability” they form schemata and when the schemata are “robust and reasonably coherent”, they are mental models (Redish, 2003, p. 24).

Notwithstanding the differences in approach and use of terms and definitions, it is useful to note the view expressed by Besson who, when considering the implications of different types of explanation employed in the field of physics, suggested that the goals of the philosophy of science are different from those of science education. “The didactic objective (of science education) is to supply resources useful for a better understanding of scientific facts, and for building a rational methodology and modern image of science” (Besson, 2010, p. 242), and with this in mind, attention is drawn to the question of the role of hands-on tasks in this endeavour.

2.3 The role of hands-on tasks in physics conceptual development

By way of a definition for the purpose of the present work, a ‘hands-on task’ is a task in which the student engages with an apparatus in order to answer a specific, physics related question (Reif & St John, 1979; Etkina & Horton, 2000).

2.3.1 The goals of hands-on tasks in teaching and learning physics

In stating a broad policy, the American Association of Physics Teachers' Committee on Physics took the view that "laboratory work is essential in the study of physics" (AAPT, 1998, p. 483) and in adopting the 'Goals of the Introductory Physics Laboratory' policy statement, it was agreed the goals in respect of laboratory work should include:

1) *The Art of Experimentation*: The introductory laboratory should engage each student in significant experiences with experimental processes, including the design of investigation.
2) *Experimental and Analytical Skills*: The laboratory should help the student develop a broad array of basic skills and tools of experimental physics and data analysis.
3) *Conceptual Learning*: The laboratory should help students master basic physics concepts.
4) *Understanding the Basis of Knowledge in Physics*: The laboratory should help students understand the role of direct observation in physics and to distinguish between inferences based on theory and the outcomes of experiments.
5) *Developing Collaborative Learning Skills*: The laboratory should help students develop collaborative learning skills that are vital to success in many lifelong endeavours.

To meet these goals, it has been suggested by Sunal (2004) that inquiry-based teaching is essential and that teachers have "to go far beyond traditional teaching strategies to create meaningful learning in students". To this end, students must engage in learning experiences that allow for the reconstruction of prior knowledge in the formulation of new science ideas and that "the underlying college science pedagogy that supports this constructivist approach to teaching and learning is an inquiry science-teaching model" (Sunal, 2004, p. 91).

Sunal goes on to suggest that several inquiry pedagogical models have been devised that centre on conceptual reconstruction and "they all fall under the general name of *learning cycles*"; examples of which have been proposed by Barnes, Driver, Karplus, Erickson, Nussbaum and Novic, Renner, and Rowell and Dawson. (Sunal, 2004, p. 93). These models have it in common that they focus on the "(cyclic) strategy of reconstruction of knowledge that involves *experience*, *interpretation* and *elaboration* in a specific sequence of learning experiences" (Sunal, 2004, p. 93). The general model of the learning cycle begins with an experience (exploration phase) in which a new science idea is introduced, this is followed by an explanation or an interpretation (invention phase) and is completed by the elaboration of the idea (expansion phase) in which the student is to apply the explanation and to "connect to the real world" (Sunal, 2004, p. 102). According to Sunal, "The expansion phase is perhaps the most important, but (is the) most overlooked part of the lesson in traditional teaching" (Sunal, 2004, p. 109).

With the goal of allowing students to see the fundamental principles of physics in action - and with the short-comings of the traditional methods of teaching physics in mind - an example of a typical approach to a model-based curriculum is that of the *Matter & Interactions* physics curriculum which includes:

a) applying the fundamental principles of physics to a wide variety of situations
b) relating microscopic properties to relevant macroscopic characteristics
c) connecting computational models to experiments, and
d) using simple error analysis when needed to distinguish between physics models. (Beichner, Chabay & Sherwood, 2009, p. 456)

In this case, the adoption of these goals leads to the development of the types of experiments (hands-on tasks) that have the following characteristics:

a) simple experiments and equipment that can evoke deep issues,
b) experimental situations that may be data-poor but analysis-rich, and
c) a series of related experiments that span the semester and that help tie various aspects of the course (theory) together (Beichner, Chabay & Sherwood, 2009, p. 456).

However, the implementation of the stated goals such as expressed in the given example is not without difficulties.

2.3.2 Difficulties in the use of hands-on tasks

If the views: a) of the American Association of Physics Teachers' Committee on Physics that "laboratory work is essential in the study of physics", and b) that hands-on tasks can play an important role in closing the learning cycle, are accepted, then it is of concern that it has been shown that in educational settings, practical work is not as effective in getting students "to use the intended scientific ideas to guide their actions and reflect on the data they collect" as it is expected it could be. (Abrahams & Millar, 2008, p. 1945). It has been suggested that although teachers design ways to help students construct new meanings and understandings, they seldom put that much effort into teaching students to engage in thinking processes, "such as identifying assumptions, evaluating the validity of information, forming good questions, planning experiments and drawing conclusions" (Zohar, 2004, p. 6).

Indeed, the view expressed by Reif and St. John more than 30 years ago that "most students cannot meaningfully summarise the important aspects of the experiments they have just completed," may still resonate today. Those authors went on to suggest that "usually (the students) recall some of their manipulations in the laboratory, but they are unable to articulate the central goal of the experiment, its underlying theory, or its basic methods" (Reif & St. John, 1979, p. 950).

The engagement with hands-on tasks, as used in teaching and learning, includes the possible complication of students requiring special tuition to acquire the technical skills required to use the apparatus in question - which may be considered to be a task in itself - and furthermore, students may also be required to make observations in an environment and/or a setting that may be confusing to them. As pointed out by Driver in *The fallacy of Induction in Science Teaching*:

> If we wish to develop an understanding of the conventional concepts and principles of science, more is required than simply providing practical experiences. The theoretical models and scientific conventions will not be 'discovered' by (students) through their practical work. They need to be presented. Guidance is then needed to help (students) assimilate their practical experiences into what is possibly a new way of thinking for them (Driver, 1983, p. 9).

More recently, difficulties regarding practical work in school science were described in a study by Abrahams and Millar who used an evaluation model that considered the effectiveness of practical work in the classroom. The study compared what the teacher had intended the students to learn with what they actually learnt, as well as comparing what the teacher intended the students to do with what they actually did. From this work it was concluded that “Practical work was generally effective in getting students to do what was intended with physical objects, but much less effective in getting them to use the intended scientific ideas to guide their actions and reflect on the data they collect” (Abrahams & Millar, 2008, p. 1945).

2.3.3 Model-based approaches to teaching and learning in laboratories

Despite the difficulties to be overcome in using hands-on tasks, various inquiry curricula with a model-based approach have been developed in which making “the correspondence between a concept or a representation and an actual object or event in the real world” (McDermott, 1991, p. 303) is made explicit.

Examples of the model-based inquiry in the laboratory component within the model-based approach curricula include, *Student-Centered Active Learning Environment for Undergraduate Programs* (SCALE-UP) (Beichner *et al.*, 2009), *Workshop Physics* (Laws, 2004), *Investigative Learning Environment* (ISLE), (Etkina *et al*., 2006), and *Spiral Physics* (D’Alessandris, 2011). A more recent example of a model-based inquiry program of this sort is *A framework for incorporating model-based inquiry into physics laboratory courses* by Zwickle, Finkelstein and Lewandowski (2013), where a key aspect of the curriculum is that the engagement is student-directed, albeit with the necessary guidance, in order to “scaffold the learning of scientific practices” (Zwickle *et al*., 2013, p. 6).

2.4 Applied strategies in model-based instruction

In this section, a selection of strategy applications in model-based instruction are reviewed to be used as a reference, but it has to be highlighted that none of these is directly comparable to the present work since the reviewed cases are applicable to situations in which modelling is being taught in a guided process. It is not known if there is equivalent published work on studies of strategies actually adopted in a model-based environment where the hands-on tasks are entirely student driven.

2.4.1 General model development as proposed by Hestenes (1987)

In proposing a modelling theory for physics instruction, Hestenes (1987), described a generalised process for model development which he suggested should be used in “the teaching of explicitly formulated modelling strategies” (p. 444). According to Hestenes, this process of general model development was based on what physicists had learned about modelling strategy “from long experience” and by this process there were four stages of modelling: *I Description*, *II Formulation*, *III Ramification*, and *IV Validation*. See Figure 2.

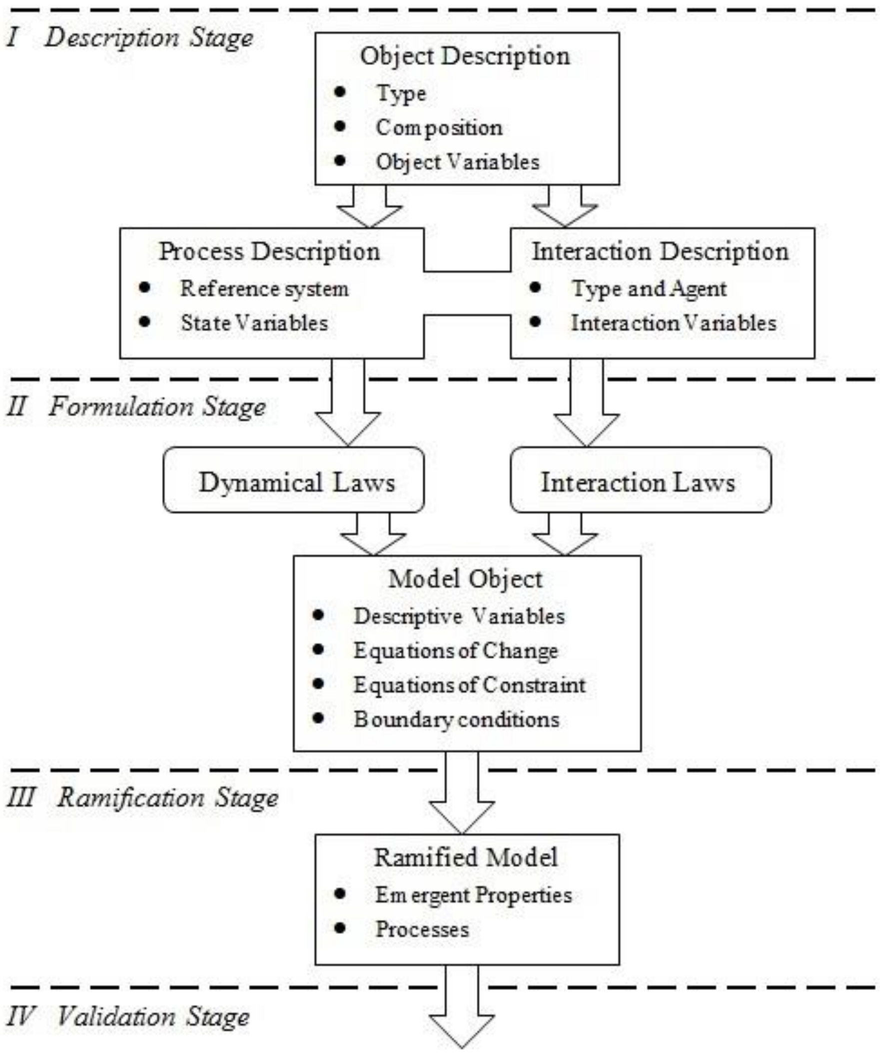

Figure 2: A proposed process of general model development (Hestenes, 1987)

According to Hestenes the main output of the Descriptive Stage is “a complete set of names and descriptive variables for the model, along with physical interpretations for all the variables” (Hestenes, 1987, p. 444). In the Formulation Stage the physical laws are applied to determine definite equations for the model object as well as any subsidiary equations of constraint. The special properties and implications of the model are worked out in the Ramification Stage, where the process is largely mathematical. And finally, the Validation Stage “is concerned with empirical evaluation of the ramified model” (p. 446). Hestenes suggests that this modelling strategy needs to be supplemented by some additional procedural knowledge, and while the developer has to provide “leeway in the order in which the steps are taken and back-tracking is often necessary” (p. 444), the strategy of the proposed general process of model development presents in a linear fashion.

2.4.2 The act of modelling as proposed by Justi and Gilbert (2002)

In considering the implications for the education of modellers, Justi and Gilbert (2002) identified a ‘model for modelling’ framework which, according to the authors, was substantially based on the work by Clement (p. 370). See Figure 3.

Apart from stating that an analysis was done on how models are produced in science, the authors do not explain how the model for modelling framework was developed or tested. However, the application of the model for modelling is described and in its broadest description it presents in four stages, although the authors do not say so explicitly; they use the terms ‘phase’, ‘stage’, and ‘step’ interchangeably in their description.

The first stage according to the model of modelling is to decide on the purpose of the model, make observations (have experience) of the phenomena to be modelled, and then to select a source for the model. The selection of the source is an analogical transfer of some existing consensus model or producing a model *de novo*. The outcome of the first stage is a mental model and the second stage is to express the mental model in a representation that is: “material, visual, verbal, mathematical”. It is suggested that the process of expressing the mental model appears to be cyclic in that the expression of the mental model may lead to it being modified. “Having produced a model (or having formed an appreciation of a scientific model) the next step is to explore its implications through *though experimentation* (italics in the original)" (Justi & Gilbert, 2002, p. 371). It is only once the mental testing of the model is complete that the final stage of empirical testing takes place. While this 'model for modelling' presents a staged, linear process, it also provides for much greater flexibility in the way in which the sub-processes are seen to be cyclic and self-correcting. The authors go on to state that "modelling is a complex process, involving many component activities" (p. 372).

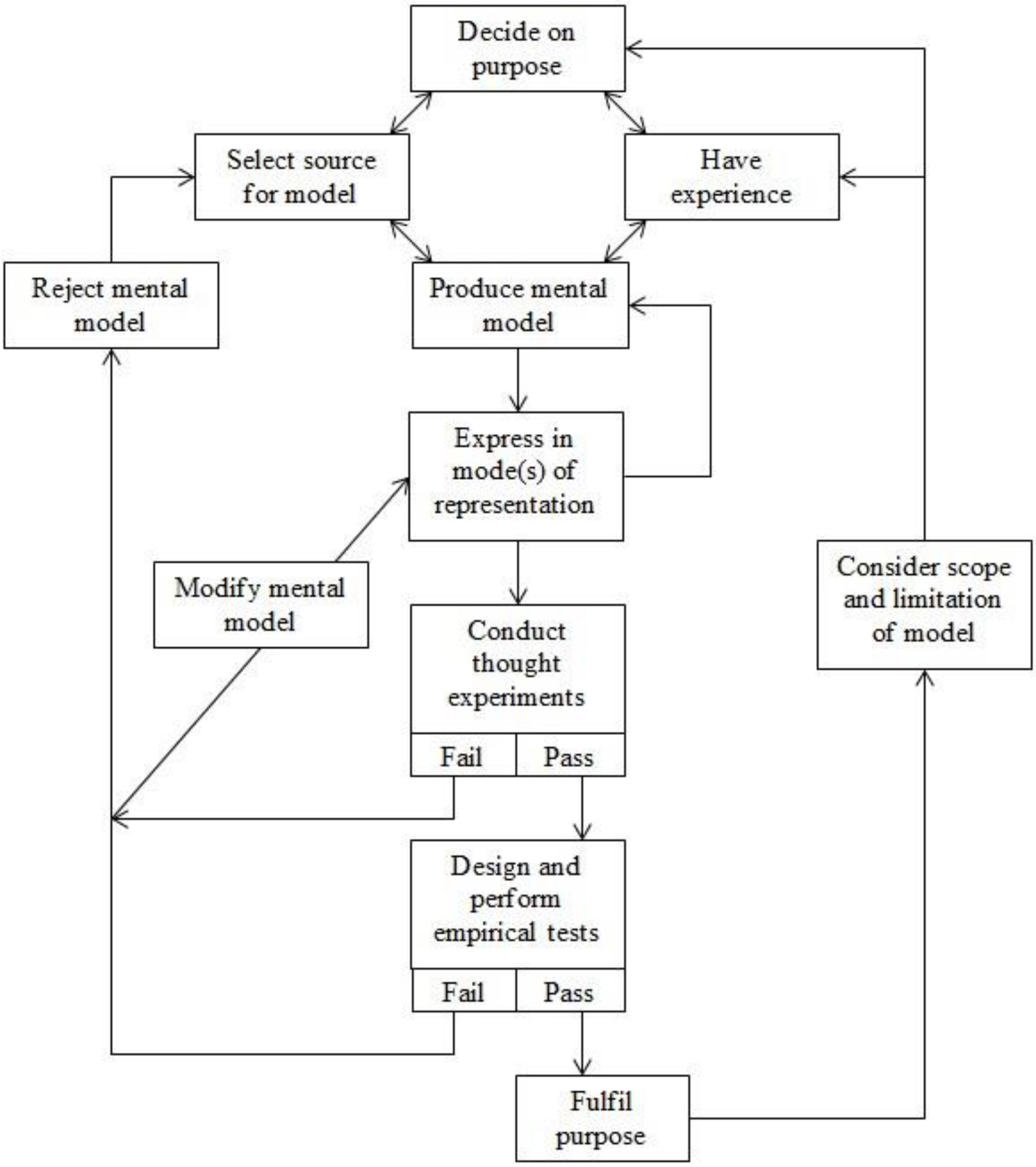

Figure 3: A 'model for modelling' framework (Justi & Gilbert, 2002)

2.4.3 Model deployment in an application activity as proposed by Halloun (2007)

In Halloun's Mediated Modelling in Science Education (2007), the author writes:

> special attention is devoted to two modelling processes that we see as scientists' primary modes of inquiry about physical realities: a) construction of a new model, corroboration included, in the context of particular real world situations in order to present a given pattern in this world, and b) deployment of an already constructed model for solving empirical or rational problems and for further knowledge development (Halloun, 2007, p. 672-673).

According to Halloun, the modelling processes of new construction development and deployment of existing models does not necessarily happen sequentially as these two complement one another. Moreover, these two modelling processes follow the same "canons of engagement" as they go "through a series of inquiry activities in both the empirical world of physical realities and related data and the rational world of scientific theory and paradigm" (Halloun, 2007, p. 673).

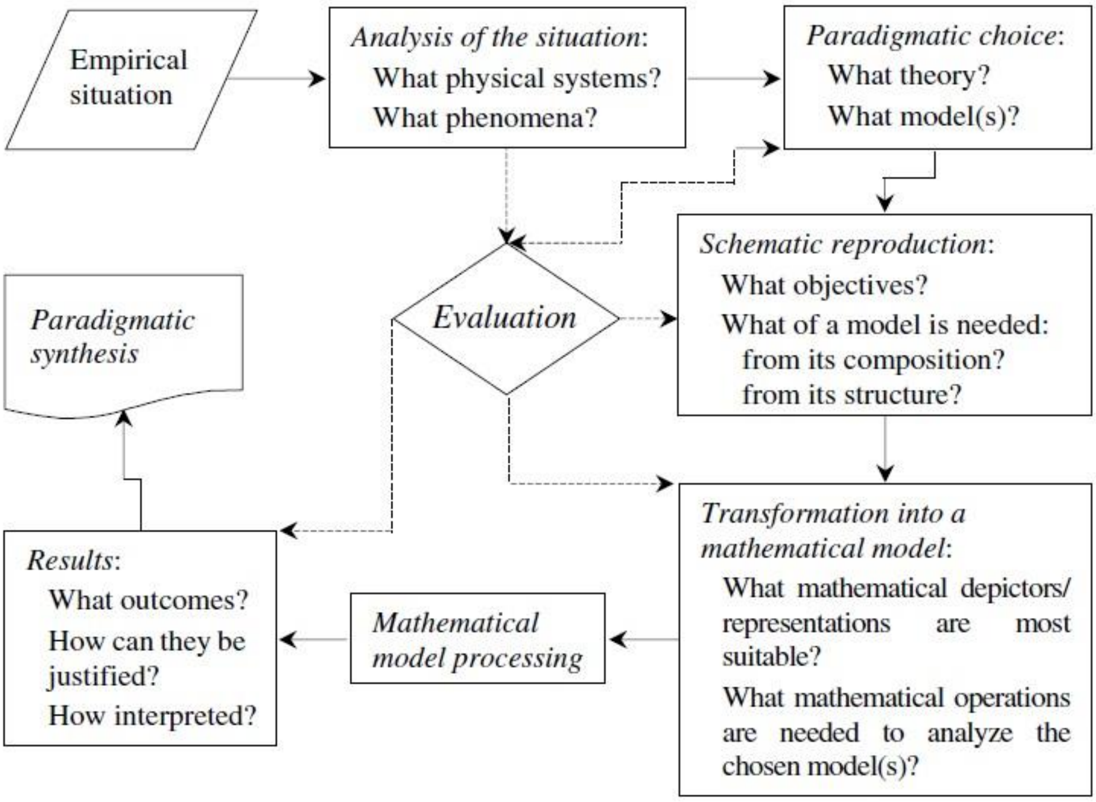

Figure 4: Model deployment in an application activity (Halloun, 2007)

Halloun proposes a “traditional” modelling scheme which is depicted in Figure 4 in which the strategy outlined in this deployment starts by analysing the “givens” of the problem “in order to choose, in an appropriate theory, the model(s) that can best represent the situation at hand” (Halloun, 2007, p. 674).

The author gives a very specific description of the process:

> Once models are chosen, and only then, one can identify the problem goals in order to pick whatever is necessary for solving the problem from the model composition and structure, and then represent the chosen components mathematically in convenient, multiple ways (diagrams, equations, graphs, etc.). A mathematical model is thereby constructed, and is subsequently processed in order to reach a solution to the problem. Every step of the way is evaluated by correspondence to the empirical situation, and in terms of the chosen theory, in order to ensure the validity and viability of the step. The process ends with a paradigmatic synthesis that recapitulates all major lessons learned in solving the problem, along with their implications on deployed models. This may include possible refinement of models and respective theory (Halloun, 2007, p. 674).

There is no indication in the referenced work as to how the modelling scheme shown in Figure 4 was derived.

2.4.4 The ISLE cycle as proposed by Etkina and Van Heuvelen (2007)

While the interactive teaching method, Investigative Science Learning Environment (ISLE), does not deal with modelling *per se*, the ISLE process does “involve observing, finding patterns, building and testing explanations of the patterns, and using multiple representations to reason about physical phenomena (Etkina & Van Heuvelen, 2007, p. 1); all of which are relevant to the present work. According to the authors, ISLE provides a general philosophy and specific activities that can be used in laboratories where students “learn to design their own experiments to test hypotheses and to solve practical problems”. The main elements in the ISLE cycle, and their logical connections, are presented in Figure 5.

In presenting the ISLE cycle, the authors suggest that “this approach resembles the processes that the scientific community uses to acquire knowledge (Etkina & Van Heuvelen, 2007, p. 6). A discussion about the various ways in which scientists acquire knowledge is given and they suggest that there are discernable elements in the process of developing ideas in science on which most agree, namely the elements of: "empirical evidence, inductive and hypothetico-deductive reasoning, coherence of ideas, the testability of ideas, and collegiality" (Etkina & Van Heuvelen, 2007, p. 23). With this in mind, the ISLE cycle is designed with three main activities in mind: 1) the observation experiment where observations are made and data are collected, 2) analysis by representing the data in multiple ways and finding patterns using inductive, analogical and hypothetico-deductive reasoning, and 3) testing the predictions made in the first steps of the cycle. In the event that the testing shows that the predictions made in the second stage were incorrect or inadequate, a cyclic process of modification is followed until a satisfactory result is achieved.

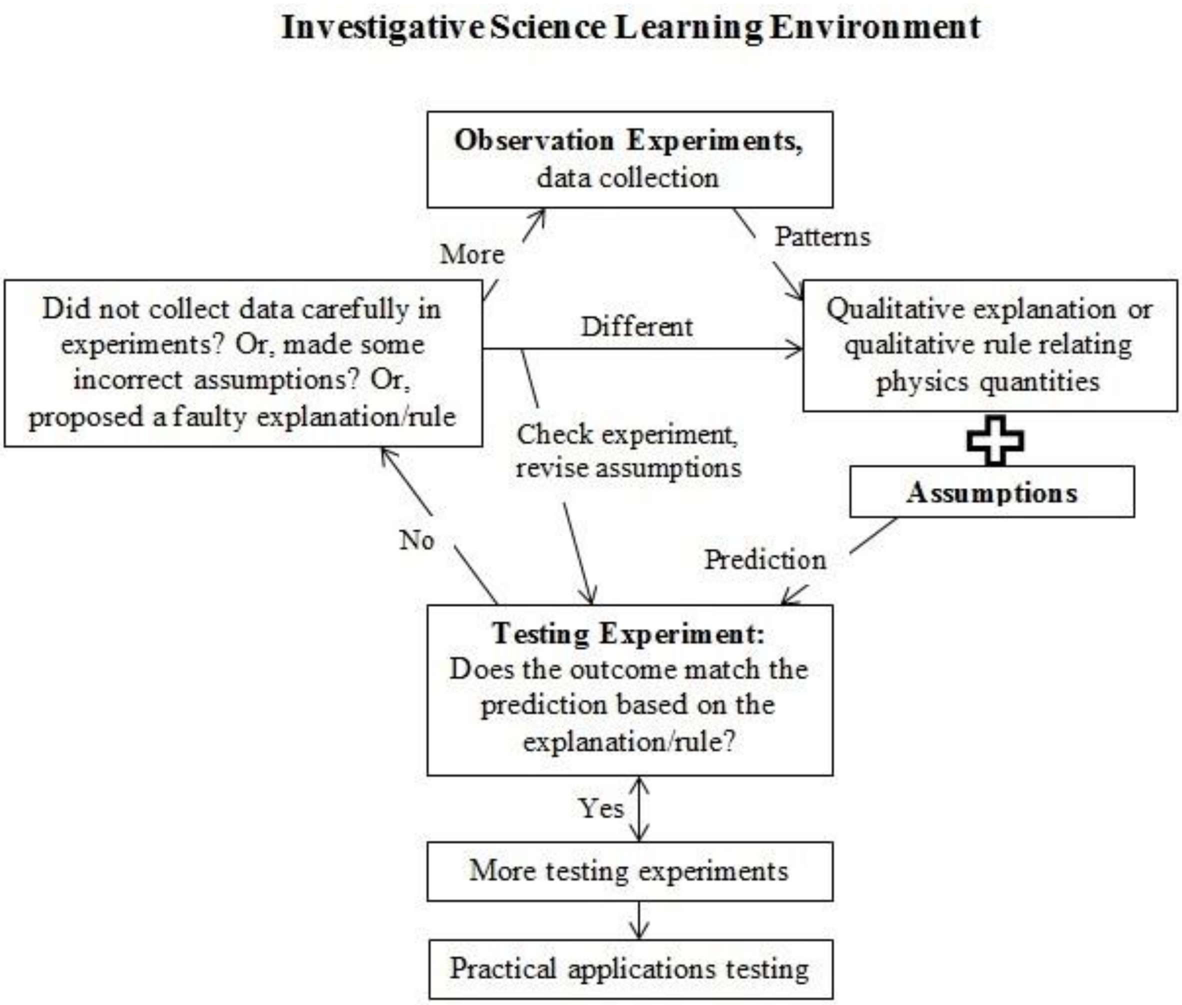

Figure 5: The ISLE cycle (Etkina & Van Heuvelen, 2007)

2.4.5 A model-based framework for physics laboratories by Zwickle *et al*., (2013)

Zwickl, Finkelstein and Lewandowski (2013), have proposed a framework that "describes how models are used in the process of experimental physics" (p. 10). The framework is shown in Figure 6 and according to the authors was inspired by Buffler, *et al*., (2008) but was expanded to reflect the research experiences of the authors.

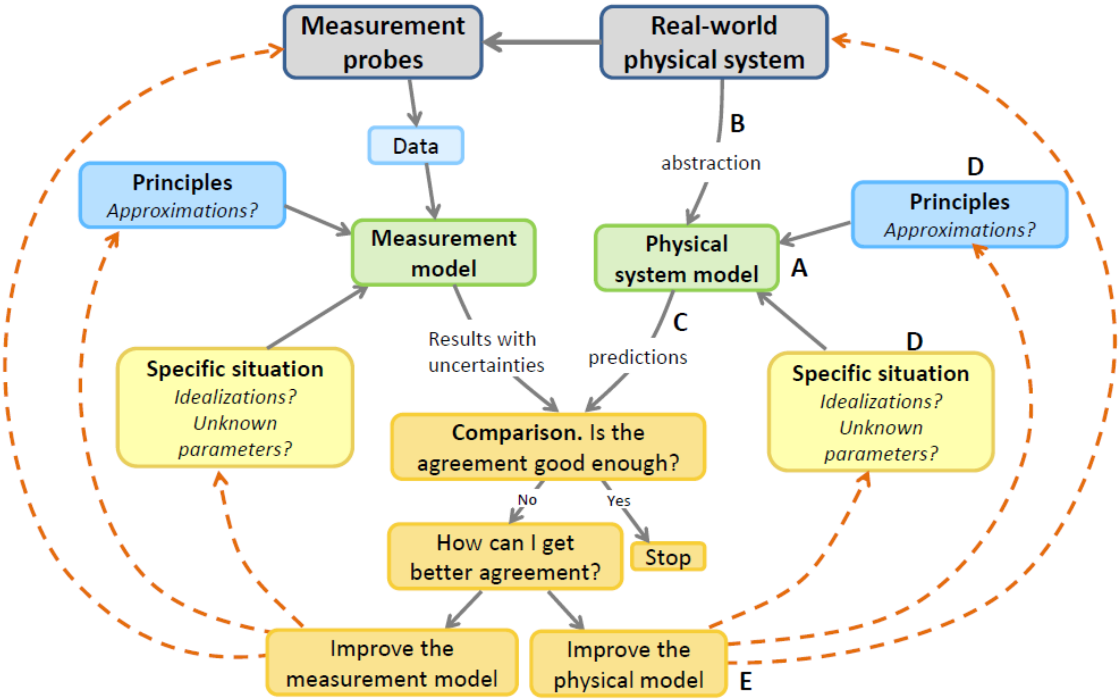

Figure 6: A modelling framework for physics experiments (Zwickl *et al*., 2013)

The framework is mirrored, left and right, to show two interlaced models, a *measurement model* and a *physical system model*. The measurement model is designed to integrate the modelling of the uncertainty associated with the measurements made during the experiment on the one hand, with the development of the physical system model that represents the physics on the other. Of relevance to the present discussion are the five steps, labelled A to E, that describe the modelling process.

According to this framework, the process begins with the creation of "an abstract model of the real-world physical system" (p. 16) when at A, a set of physical principles are combined with a specific situation, and then, at B, all the parameters and quantities in the model are connected to aspects of the real system. This mapping is considered to be a key part of the process and is often done using diagrams and guidance as necessary (for the student) as the model needs to be interpreted.

At C, the modelling “moves beyond basic identification and qualitative description, and requires students to make specific predictions that can be compared with measurements” and as the authors point out, “this is not a trivial task because there are multiple ways to represent data and theory” (p. 17).

The limitations of the model are identified at D, where it is considered that shortcomings in the assumptions in the model may arise in regard to “*principles*, which may be approximate, or in the *specific situation*, which may contain idealisations and unknown parameters (italics in the original)” (p. 18). Finally, at E, the model is refined “in order to reconcile any differences between the predictions and the measurements”. The refining process may include “activities like calibrating the measurement system, making the model more sophisticated to include a particular systematic error source, or modifying the apparatus to make a simpler model more valid” (p. 19).

2.5 Cognitive processes, epistemologies and problem-solving strategies

Having considered models and modelling from the epistemic as well as the educational points of view, attention is drawn to topics that are relevant to the present work, but are of a more general nature.

2.5.1 Cognitive & metacognitive processes

The cognitive and metacognitive processes that are reviewed in this section are chosen so as to provide a framework for considering possible mechanisms that may be relevant to the way in which students' problem-solving strategies may evolve and how they may be applied. Particular reference is made to the suggestion that model-based reasoning (Nersessian, 2006) can be seen as a specific type of reasoning which would in turn suggest that there are strategies peculiar to that type of reasoning.

2.5.1.1 Individual cognitive processes in respect of mental models

Several strands of research have emerged that consider the theoretical notions of 'mental models' and 'mental modelling', one of which considers the semantic information in logical reasoning by Johnson-Laird (Nersessian, 2008). Johnson-Laird offered, in 1983, "a unified and explanatory theory of distinctive cognitive phenomena" (Greca & Moreira, 2000, p. 2) and by this explanation it was proposed that there are at least two, and possibly three[2], types of mental representation used in cognition. The question of the actual mental representations that are used in the forming and manipulation of mental models is not relevant to the present work so these will not be explored here, although cognitive and metacognitive strategies, which are indeed relevant, are addressed later in the section dealing with cognitive processes (below). Suffice it here to say that it is considered that "mental models are working models of situations in/of the world, and that through their mental manipulation we are capable of understanding and explaining phenomena" (Greca & Moreira, 2000, p. 4).

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[2] In later work (1989), Johnson-Laird reduced these to two types since images are a "special sort of model – a two dimensional representation that is projected from a three-dimensional model" (Nersessian, 2008, p. 101).

Moreover, it has been suggested that mental models are characterised by their recursive nature in that they are never complete but continue to change in the process of discourse. Further, it has also been suggested that depending on the subject's knowledge and his/her ability, the perception of real world phenomena is dependent upon the kind of mental models the individual is able to construct. At the same time, the constraints to mental model construction - which are products of the individual's prior knowledge - "derive from the perceived or conceived world structure, from ontological beliefs, and from the need of maintaining the cognitive system free of contradictions" (Greca & Moreira, 2001, p. 109).

As has been noted earlier, several independent strands of cognitive research emerged with the introduction of the notions of the 'mental model' and 'modelling', two of which are: a) the strand that considers the nature of mental representations in working memory and b) the strand that considers the role of mental representations in long-term memory (Neresessian, 2008, p. 94). Of these, the strand relevant to the present work is that which considers the effects of semantic information in logical reasoning.

Johnson-Laird's 1983 monograph in the field of cognitive psychology, *Mental Models*, does not concern itself with the neuronal complexity of the brain but instead views the brain from a functional point of view. Indeed, Johnson-Laird considers the brain as logical 'black box' that works in a discernible, functional way and in his work it is argued that humans are incapable of a formal logic, listing the following to illustrate the point:

1) people make fallacious inferences, i.e., people take invalid logical steps,
2) logicians have defined various forms of logic; none of which are identified as being employed by the mind,
3) there appears to be no method by which people have the capacity to formulate a logic,
4) there appears to be no method by which a logic can arise in the mind,
5) human reasoning is not immune from "the content of the premises" the implication being that the 'logic' that a person would apply in one setting may

be different from that applied in another setting, even though the problem may be the same, and

6) people follow extra-logical heuristics when they make spontaneous inferences. They appear to be guided by the principle of maintaining the semantic content of the premises but expressing it with greater linguistic economy. i.e., people use simplified analogies. (Johnson-Laird, 1983, p. 39.)

Johnson-Laird's thesis is that people's reasoning "ordinarily proceeds without recourse to a mental logic with formal rules of inference", instead, people use a variety of deductive inferences where "the simplest inferences depend on the interrelations between propositions, not on their internal structures". A concept relevant to the present work is that according to Johnson-Laird, humans do not think by moving from one verified logical statement to the next, but that humans reason by: a) moving from one proposition to the next through inferences that allow for the making of decisions, b) the taking of courses of action, c) the evaluation of assumptions and hypotheses, d) the pursuance of arguments and negotiations, e) the evaluation of evidence, f) the solving of problems, and g) the development of understanding (Johnson-Laird, 1983, p. 41)

"Philosophers have generally taken propositions to be the conscious objects of thought – those entities that we entertain, believe, think, doubt, etc." (Johnson-Laird, 1983, p. 155) and a working definition of inference is given as "a process of thought that leads from one set of propositions to another. Typically, it proceeds from several premises to a single conclusion, though sometimes it may be an immediate step from a premise to a conclusion" (Johnson-Laird, 1983, p. 23).

In applying deductive inferences, two sorts of inference are identified, explicit inference and implicit inference. Inferences that tend to be time consuming, i.e., those that are at the forefront of awareness and "require a conscious cold-blooded effort" are considered to be explicit. While inferences that "underlie a more mundane process of intuitive judgement and the comprehension of discourse, tend to be rapid, effortless, and outside conscious awareness, are implicit" (Johnson-Laird, 1983, p. 127). According to Johnson-Laird's thesis, both explicit and implicit inferences are made in generally the same way with the distinction that explicit inference depends on “searching for alternative models that may falsify putative conclusions” while implicit inferences depend on “constructing a single model” (Johnson-Laird, 1983, p. 144). In making inferences, people follow extra-logical heuristics to find out what the ‘decision’ is or what the ‘answer’ may be. In order to make a successful inference – and so to move from one proposition to the next – people construct mental models of the states of affairs as they see them and then by simplifying the premises which constitute the proposition and by substituting truth values as appropriate, the inference is made.

Johnson-Laird suggests the process of inference is characterised by: a) the ability that people have to recognise a disjunction in a propositional statement and to know that if it is not ‘one’ then it is the ‘other’, b) the ability to evaluate complex proposition statements by substituting truth values in the components of the propositions, and c) the ability to ensure that the new propositional statement is free from contradictions (Johnson-Laird, 1983, pp. 51). Further, when the required inference involves three propositions, there are limitations in the mind where – apart from memory overload – people do not “spontaneously examine combinatorial possibilities in a systematic fashion” (Johnson-Laird, 1983, p. 46).

2.5.1.2 Metacognitive processes

Metacognitive processes have been defined as “conscious and deliberate thoughts that have other thoughts as their object” (Hacker, 1998, p. 8). Hacker goes on to suggest that, metacognitive procedures must always be active and conscious and must not only be potentially controllable, but potentially reportable. And while some authors have suggested that metacognition may not have to be conscious and deliberate, this distinction has not been expanded upon in this review as it is not considered to make a relevant contribution to the framework required in the present work.

Of relevance to the present work however, is that the term ‘metacognition’ may be used in two senses: a) with reference to one’s knowledge and content of the cognitive system, and b) with reference to one’s control of the cognitive system (Zohar, 2004, p. 3). In this study, metacognition is used in the second, controlling, sense; which is in agreement with Hacker, in that it refers to those conscious and deliberate thoughts that have other thoughts as their object.

2.5.1.3 Distributed cognitive processes and model-based reasoning

According to Nersessian (2006), problem-solving episodes in science have often involved many researchers working on the same problem over temporal and spatial distances and in this sense, the development of modelling practices became communal efforts which suggests that 'cognition' needs to be seen as being "situated in environments and not just in minds." This view suggests that cognition is '*embodied*', '*enculturated*'(sic) and '*situated*' and consequently

> cognitive processes cannot be treated separately from the contexts and activities in which cognition occurs. *ibid*. 'Cognition', thus, comprises a complex system, "stretched over" what has been thought of as "internal" and "external" representations and processes. *ibid*. (the individual) minds are parts of distributed cognitive systems, integrated with bodies and integral to the system's cognitive capacities (Nersessian, 2006, p. 701).

By this interpretation, cognitive capacities such as memory, reasoning and problem-solving are attributed to the communal, or distributed cognitive system although the human agent is still central to its functioning. Of particular relevance to the present work is that by this view, while the mental model may be considered to be located in the minds of the individuals involved, the physical model may be considered to be located in the communal cognitive system. However, as made clear by Nersessian, when researchers engage in modelling systems, "Each mental model is both an individual and a community achievement. Each physical model is constructed by this community to represent and perform as an aspect of the (modelled) system" (Nersessian, 2006, p. 705). In this distributive cognitive process, models from mathematics and physics may inform the construction while the entire model system comprises interlocking physical and mental models.

The above view would appear to be in agreement with that expressed by Greca and Moreira that when considering the role of the individual in the process of understanding physical models, "we should not put aside the social aspect implied in mental model construction, particularly in physics, which is a socially constructed and transmitted product" (Greca & Moreira, 2001, p. 119).

In considering the kinds of reasoning that are involved in this process it is necessary to define instances of model-based reasoning. According to Nersessian, for something to be recognised as an instance of model-based reasoning it must involve: 1) the construction or retrieval of a model, and 2) inferences that have been derived (should have been derived) through the manipulation of a model. The inferences so derived may be specific or general. By 'specific' it is meant that the inferences may apply to the particular model in question while by 'general' it is meant that the inferences made may apply to a type of model that represents a class of models. In either case, "in model-based reasoning, problem-solving takes place through the construction of models *of the same kind* (italics in the original) with respect to the salient dimensions of target phenomenon (and) inferences are derived through manipulation of the model" (Nersessian, 2006, p. 706).

Nersessian suggests:

> the kinds of (model-based) reasoning processes include, although not limited to (or ordered):
>
> - abstraction: limiting case, generic, idealisation, generalisation,
> - simulation: inferring outcomes or new states via model manipulation (mental or physical),
> - evaluation: goodness of fit, explanatory power, implications (empirical, mathematical), and
> - adaptation: constraint satisfaction, coherence, other relevant considerations,

finally concluding that model-based reasoning occurs in a 'distributed cognitive system'. The important inference is that physical and mental models involve co-construction and manipulation, and thus "the reasoning processes take place not just in the mind of a single researcher but across researchers and artefacts within the problem space of the laboratory" (Nersessian, 2006, p. 706-708).

Given that "models are built and evaluated on the basis of relational comparisons (where) mappings and transfer between models and target need to meet (established) criteria", it can be said that, "*model-based reasoning is closely bound up with analogy* (italics in the original)" (Nersissian, 2008, p. 184).

2.5.2 Theory-ladenness influencing scientific processes

N. R. Hanson's *Patterns of Discovery* (1958) initially considered only the application of theory-ladenness to perceptual observation, but it has since been applied to other contexts of human cognition as researchers have considered whether or not theory-ladenness is an exclusively perceptual process (Bogen, 2013). In this regard it has been suggested by Brewer and Lambert that not only is observation and theory deeply interwoven but that theory-ladenness may in turn influence a broad range of scientific processes including:

> a) *Perception*: The narrow sense of conscious, visual experience has been shown to be 'cognitively penetrable,' i.e., vision can be influenced by other cognitive processes and beliefs. The authors illustrated the cognitive penetrability of vision by the lines in the Müller-Lyre figure where, even after measuring them and having found them to be the same length, the observer continues to perceive them as being of different lengths.
> b) *Attention*: Those events to which attention is paid, i.e., those under cognitive control, undergo different cognitive processes compared to simultaneous events to which attention is not being paid. MRI evidence suggests that non-attended events are not perceived by the higher cortical centres.
> c) *Data interpretation*: Providing a theory for data can lead to much greater comprehension and memory for stimulus material.
> d) *Data production*: Approaches to the selection and design of experiments are theory based.
> e) *Memory*: Human memory is strongly influenced by beliefs. Information related to an individual's theory has been shown to be easier to recall and less likely to be distorted.
> f) *Scientific communication*: The selection of what is communicated is theory-laden. (Brewer & Lambert, 2001, p. 177).

Of particular relevance to the present work is a study cited by Brewer and Lambert in which it was concluded by Brewer and Chinn that when scientists analyse data that is in conflict with their theories, they may, "adopt a variety of strategies to avoid the need to change their theories; for example, scientists (may) ignore data, reject data, exclude data, hold data in abeyance, and reinterpret data" (Brewer & Lambert, 2001, p. 181).

2.5.3 Student epistemologies

Two aspects of student epistemology are referred to is this study. Firstly the notion that students' epistemologies are stratified and, by implication, that this may have a limiting effect on student engagement; and secondly the notion that students may exhibit unexpected epistemological resources.

2.5.3.1 The stratification of epistemologies

Based on the original work done by Carey and Smith (1993), Smith and Wenk (2006) went on to describe a 3-level topology for student epistemologies which may be considered a ranking of the sophistication of their epistemologies. Those researchers describe the 3 levels as follows:

> **Level 1**: An epistemology in which students have no appreciation of the role of scientists' ideas in guiding activities and experiments, of experimental results (or other data) that provide evidence for ideas, or of any uncertainty in scientific knowledge. (By this epistemology it is believed that) scientists simply make (local) observations of what happens, do tests, find out what works or how to do something correctly, and amass a true collection of beliefs about the world.
>
> **Level 2**: An epistemology in which students are open to the view that scientists are fundamentally concerned with understanding how things work, or why things happen, (they are) not just concerned with knowing what happens or how to do things. (By this epistemology) the two new notions that emerge are the ideas of 'explanation' and 'hypothesis testing', both of which support making a fundamental differentiation between scientists' ideas and results.
>
> **Level 3**: An epistemology in which students view a theory as a coherent network of interrelated concepts (or causal relationships) that informs all aspects of inquiry – the questions raised, the methods used, and the formation of specific testable hypotheses. (By this epistemology students believe that) the process of hypothesis testing may ultimately lead to results that challenge the framework theory. ibid. In this sense the process of evaluating hypotheses is not only constrained by available data but also by available theories. Thus, even well-supported theories may be revised or changed
>
> (Smith & Wenk, 2006, p. 749-750).

2.5.3.2 Epistemological resources in problem-solving

In the paper, *On the Substance of a Sophisticated Epistemology,* (2001), Elby and Hammer argued that a distinction should be made between the correctness of an epistemological belief and the productivity of an epistemological belief (p. 555), going on to offer a critique of the consensus view (traditional view) about what constitutes epistemological sophistication. Their approach was to consider the benefits and/or disadvantages of the productivity of the epistemology as opposed to its correctness for each of the following: a) Certainty vs. Tentativeness, b) Realism vs. Relativism, c) Authority vs. Independence and d) Simplicity vs. Complexity. In this work the authors concluded that "productive epistemological beliefs – ones that help students learn – sometimes differ from correct epistemological beliefs," and that, "A sophisticated epistemology does not consist of blanket generalisations that apply to all knowledge in all disciplines and contexts" (Elby & Hammer, 2001, p. 565).

The above was expanded upon in, *Tapping Epistemological Resources for Learning Physics,* by the same authors (2003) and in the paper on tapping epistemological resources it was suggested that, "Teachers and curriculum developers regularly assume, implicitly, that students already possess productive epistemological resources that can be triggered by effective instruction" (Hammer & Elby, 2003, p. 54), and that these "epistemological resources may serve the role of helping activate metacognitive resources; or they may turn on in response to metacognitive action" (p. 57). However, exactly what these epistemological resources may be is not clear and the authors report, "In our view, research on epistemologies has yet to reflect the depth of insight inherent in teachers' and curriculum developers' strategies and designs (of instructional tools)", while stating,

> our aim is to identify specific areas of expertise relevant to learning physics, to devise strategies that help students draw on that expertise, and to refine our understanding of its nature toward a more specific account of epistemological resources (Hammer & Elby, 2003, p. 59-60).

Of particular relevance to the present work is the conclusion by the researchers that students “almost certainly have resources for understanding *rule systems*, such as sports and games.” They have “abundant informal experience working with representations and representational systems” and “students’ skill at construction suggests that they also have resources for understanding the actions of checking, repairing and refining” (Hammer & Elby, 2003, p. 60-61).

2.5.4 Strategies in problem-solving

A strategy, as relevant to the present work, is defined in this section and then two frameworks for the application of strategies in problem-solving situations are reviewed by considering two approaches: a) that proposed by Goodson (2000) in which it is suggested that there are 5 components in the process of problem-solving in complex situations, and b) that proposed by Moseley, Elliot, Gregson, and Higgins (2005) in which it is suggested that the cognitive skills required to carry out the specific tasks should be delineated from the more general ‘strategic and reflective thinking’ skills that are required to manage the process of problem solving.

2.5.4.1 Strategy defined

Strategies involve the formulation of overall plans and the execution of those plans and the key distinction between a plan and a strategy is that a strategy is a cognitive engagement at a higher level than a plan (Scott, Asoko & Driver, 1991). In this sense, the employment of a strategy may be described as a metacognitive process - in its simplest description, it is the plan behind the plan.

2.5.4.2 Goodson – Strategies for Complex Thinking Skills

According to Goodson, “metacognitive strategies have been classified as complex thinking with the focus on their executive control function – evaluating, planning, and regulating thinking processes. Some metacognitive strategies may be considered simple thinking skills, while others would be complex. Metacognitive strategies include: a) problem finding and the linkage of problem finding, b) creativity through the actions of planning, c) self-monitoring of progress, and d) self-adjustment to thinking strategies" (Goodson, 2000, p. 167).

These are skills that encompass those in the higher order categories of the cognitive domain of Bloom's Taxonomy of Educational Objectives (Bloom, 1956) and more specifically, these are skills that involve "the application of at least two rules or principles to a situation with multiple factors." *ibid*. "It requires going beyond applying routine rules, beyond the routine application of previously learned knowledge. It may involve the putting together of certain rules that may not have been applied to previous similar situations" (Goodson, 2000, p. 166). By this model there are 5 components of problem-solving in complex thinking processes, namely:

1) *Authentic life situations*: A real-life situation in which the student is confronted with some multi-facetted problem in which there may be, among other difficulties, ambiguities, confusions, doubts, obstacles, questions and uncertainties.
2) *Complex thinking skills*: Those multidimensional skills in which more than one rule is required to manage the situation, or in which the student is required to transform known concepts in order to fit the given situation.
3) *Interactive prerequisites*: These are the simpler 'building blocks' needed to feed into the process of complex thinking. i.e., these are: a) content knowledge, b) simple thinking skills (involving a single rule), and c) appropriate dispositions and habits. Appropriate dispositions and habits are personal traits such as attitude, ability to adapt, risk aversion, persistence, self-monitoring, interpersonal and intrapersonal skill, and linguistic and logic-mathematical abilities among others.
4) *Connecting networks and operations*: These are the bridging mechanisms required to interlace the interactive prerequisites and the facets of the real-life situation that will allow for the expression of the outcome of the complex thinking process. Techniques that are of relevance here are: a) 'linkages' that make it possible for the student to extend prior learning to the new context, b) the holding of 'schemata' to provide architecture for organising new thoughts, and c) guidance to the learning in the early stages of the engagement.

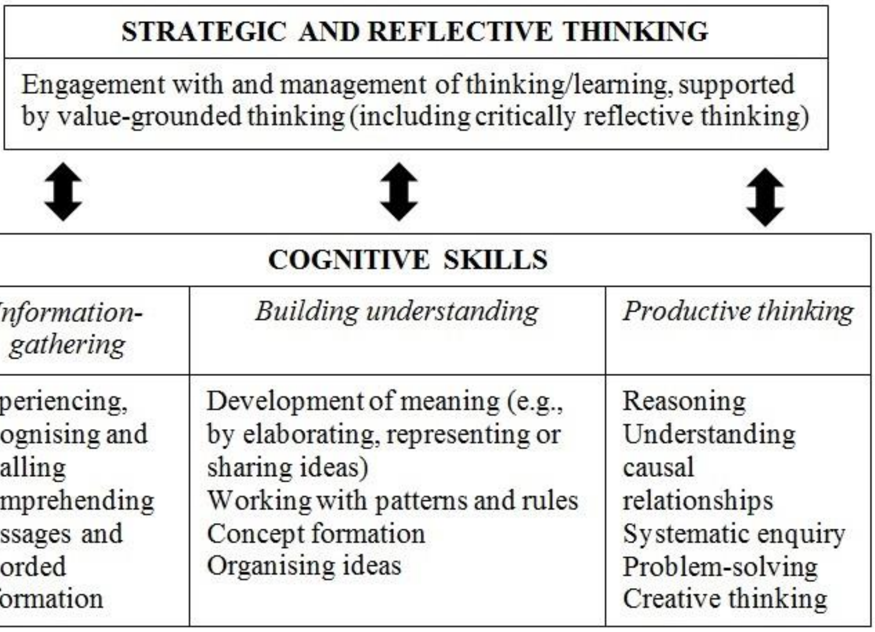
5) *Teaching and learning strategies*: Those strategies that prompt the actions in the engagement and which ultimately define the outcome of the engagement.

(Goodson, 2000).

2.5.4.3 Moseley Elliot, Gregson, and Higgins – Thinking Skills Frameworks

The framework proposed by Moseley *et al*. (2005), was formulated as the result of a systematic review of ‘Thinking Skills Frameworks’ and the schematic diagram of their deliberation is reproduced in Figure 7.

As can be seen from Figure 7, Mosley *et al*. have delineated what they refer to as the application of cognitive skills, those skills to do with information gathering, building understanding and productive thinking, from metacognitive skills, those skills that concern “awareness and control, not only of cognitive processes, but also of the processes relating to motivation and affect” (Moseley *et al*., 2005, p. 378).



STRATEGIC AND REFLECTIVE THINKING

Engagement with and management of thinking/learning, supported by value-grounded thinking (including critically reflective thinking)

COGNITIVE SKILLS

Information-gathering	*Building understanding*	*Productive thinking*
Experiencing, recognising and recalling Comprehending messages and recorded information	Development of meaning (e.g., by elaborating, representing or sharing ideas) Working with patterns and rules Concept formation Organising ideas	Reasoning Understanding causal relationships Systematic enquiry Problem-solving Creative thinking

Figure 7: Role of strategies in problem-solving (Moseley *et al*.)

The reason given by Moseley *et al*. for the delineation of cognitive and metacognitive skills is two-fold. Firstly it is assumed by those researchers that the cognitive processes of *Information gathering*, *Building understanding* and *Productive thinking* are phases that the student would have to work through while the metacognitive process of strategic and reflective thinking needs to be employed in all phases. And secondly, the delineation is because there is a perceived difference in the degree of conscious control that has to be exercised in the application of: a) *Strategic and Reflective thinking*, compared to b) *Cognitive skills*.

Indeed, Moseley *et al*. suggests that it is possible for actions that form part of the cognitive skills category to become ‘automatised,’ (*sic*). Of particular relevance to the present work is the note in the Moseley *et al*. report to the effect that the students’ engagement with the cognitive components of the task do not have to be undertaken in any particular order, suggesting that the problem-solving process may begin at any phase . The relevant note is quoted at length.

> The three components within the cognitive skill part of the framework do not always feature in a simple linear fashion; for example, it is possible to go straight from information gathering to productive thinking, without a phase of building understanding. Although information gathering is necessary to build understanding or ensure productive thinking, it is not necessarily a simpler or less conscious process. Neither does it feature only as a first phase of an action. While most recognisable thinking process would appear to involve a series of overlapping phases involving information gathering at the outset, a gradual building of understanding and, ultimately, productive thinking, there are likely to be many occasions when learners will come to realise that they need to acquire more information or revise their initial understandings. (Moseley *et al*., 2005, p. 379).

2.6 Strategies employed in computer and theoretical problem solving

In order to give some perspective on work that has been done in the field of research strategies employed when engaged with similar problem-solving situations, two pertinent studies were considered. The first has to do with the solving of practical programming problems (Klahr & Dunbar, 1988), and the second to do with a theoretical modelling problem (Clement, 2009). In the case of Klahr and Dunbar the problem-solving strategy is characterised by the search through a ‘dual space’, i.e., an ‘experimental space’ and/or a ‘hypothesis space’, while in the case of Clement the subjects’ engagement when modelling a theoretical physics problem is characterised primarily by two strategies of analogy, namely those of ‘modelling by transformation’ and ‘modelling by association’.

In reviewing the findings of the work by Klahr and Dunbar as well as that of Clement, it may be noted that there is an equivalence to be found in the work of Halloun who, in describing general modelling strategies in *Modeling Inquiry*, has stated,

> Special attention is devoted to two modelling processes that we see as scientists' primary modes of inquiry about physical realities: a) construction of a new model, corroboration included, in the context of particular real world situation in order to represent a given pattern in this world, and b) deployment of an already constructed model (Halloun, 2007, p. 672-673).

2.6.1 Dual Space Search (SDDS) strategies by Klahr and Dunbar

Klahr and Dunbar proposed the model of 'Scientific Discovery as Dual Search' (SDDS) in which it was suggested that scientific reasoning could be characterised by a search in one or both of two 'problem spaces': i) a hypothesis space and ii) an experimental space (Klahr & Dunbar, 1988). In developing this problem-solving model, the researchers identified two main strategies that are used by the problem solver: "one strategy was to search memory, and the other strategy was to generalise from the results of the previous experiment" (p. 1). Segmentally, it may be considered that the findings of this research by Klahr and Dunbar may be described as producing a mechanistic explanation in that the language used is computer orientated as is illustrated by the use of terms like 'searching memory.' However what is significant is that the researchers expand on the explanation of these two SDDS strategies by comparing them to strategies identified by Bruner, Goodnow and Austin (1956).

Bruner *et al.* are cited as having observed two basic strategies (used in similar research situations), namely those of 'successive scanning', and 'focussing'. By the former strategy the students scan through and test each possible hypothesis, one at a time, in the hypothesis space. In the latter case, students focus on one hypothesis and change the values of instances, one at a time, in the experimental space. It is also suggested that students will adopt one or other of these strategies because of the "cognitive strain or short-term memory load'; going on to suggest that,

> Subjects who can construct the correct frame from long-term memory are 'Theorists', while those who are unable to construct the correct frame from the information in long-term

> memory are ‘Experimenters’, and must search the experiment space (Klahr & Dunbar, 1988, p. 45).

Further, the researchers suggest that the Theorist/Experimenter distinction is analogous to the Model-driven versus Data-driven strategies identified in Artificial Intelligence (AI) problem solving, as well as being analogous to the fault finding strategies identified by Rasmussen (cited, 1981), in which it was shown that some operators search the hypothesis space by considering a set of symptoms that could bring about the observed condition, while other operators would simply search the experiment space to try and find the faulty component by trial and error. Klahr and Dunbar have proposed that the choice of strategy depends on the amount of knowledge about each of these domains the operator has, concluding, “Experts tend to search the hypothesis space, and novices tend to search the experiment space” (1988, p. 45).

2.6.2 Analogy strategies by Clement

According to Hestenes (2006), “an analogy is defined as a *mapping of structure* from one domain (*source*) to another (*target*). The mapping is always partial, which means that some structure is not mapped. Analogy is ubiquitous in science, but often goes unnoticed” (p. 9). Hestenes goes on to define three kinds of analogy: 1) *conceptual analogies*, which relate the differences and similarities between models of different systems or processes, 2) *material analogies,* which relate the material equivalence in structure of different systems or processes, and 3) *referential analogies*, which relate the model of a system or process to that system or process (Hestenes, 2006, p. 9).

Although Clement uses the word ‘model’ in the title of, *Creative model construction in Scientists and Students* (2009), models as have been defined in the present work are not central to Clement’s thesis. Indeed, Clement uses the word model quite loosely and when it appears for the first time in the heading to section 6.3.4 of that work, it is introduced as, “Defining Models: A thorny issue” (p. 74). In that work Clement goes on to describe a model as a ‘scientific mental model’, which, in the context of the present work, would perhaps be described as a ‘physical and mental model combination’. Nevertheless, Clement’s use of the word ‘analogy’ - which appears to be in line with the definition by Hestenes above - is more closely described and for the most part, wherever he has used the word ‘model’, it appears as if ‘analogy’ can be substituted without a loss of meaning. Indeed, Clement writes, “I will refer to all relevant analogies, explanations, and theoretical models collectively as *scientific models* construed broadly” (Clement, 2009, p. 74). Using that as a point of departure, it is considered reasonable that the strategies described by Clement in developing analogies, are transferable for the purposes of comparison to the present work.

Clement uses the word ‘method’ when describing the way in which analogies may be generated. However, in the present work, the methods described by Clement are considered to be the equivalent of strategies because they are metacognitive in nature and function in the way in which strategies have been defined in the present work. According to Clement, the methods (strategies) by which analogies (models) are ‘generated’ may be classified in four ways:

1) *Via a formal principle,* e.g., conservation laws: This is a method (strategy) whereby the subject generates the analogy through the application of physics, but other than to note that it seldom used, Clement does not discuss this method in detail in the first section of his book.
2) *Via a transformation*: This is a method (strategy) whereby the subject starts with the problem situation and transforms what they observe (perhaps by idealisation and approximation) into a suitable analogy. *Perforce*, this analogy is “close to” the actual problem situation.
3) *Via an association*: This is a method (strategy) whereby the subject starts with an analogy that worked in some other, similar problem situation and then that analogy is adapted to match the present problem situation. This may result in the adopted analogy being “far from” the actual problem situation.
4) *Unclear*: The title of the method (strategy) speaks for itself

(Clement, 2009, p. 37-42).

Of the four methods by which analogies may be generated as suggested by Clement, the examples and discussion presented in his book shows that the analogies generated through transformation and association far outweigh the other two.

Clement also uses the terms ‘significance’ and ‘spontaneity’ to group the analogies that were generated by one of the four methods listed above and these groupings are illustrated in Figure 8. Note that a significant[3] analogy is one that leads to a “serious attempt” to actually solve the problem while a spontaneous analogy is one that the student comes up with, rather than an analogy that is presented (given) to the student.

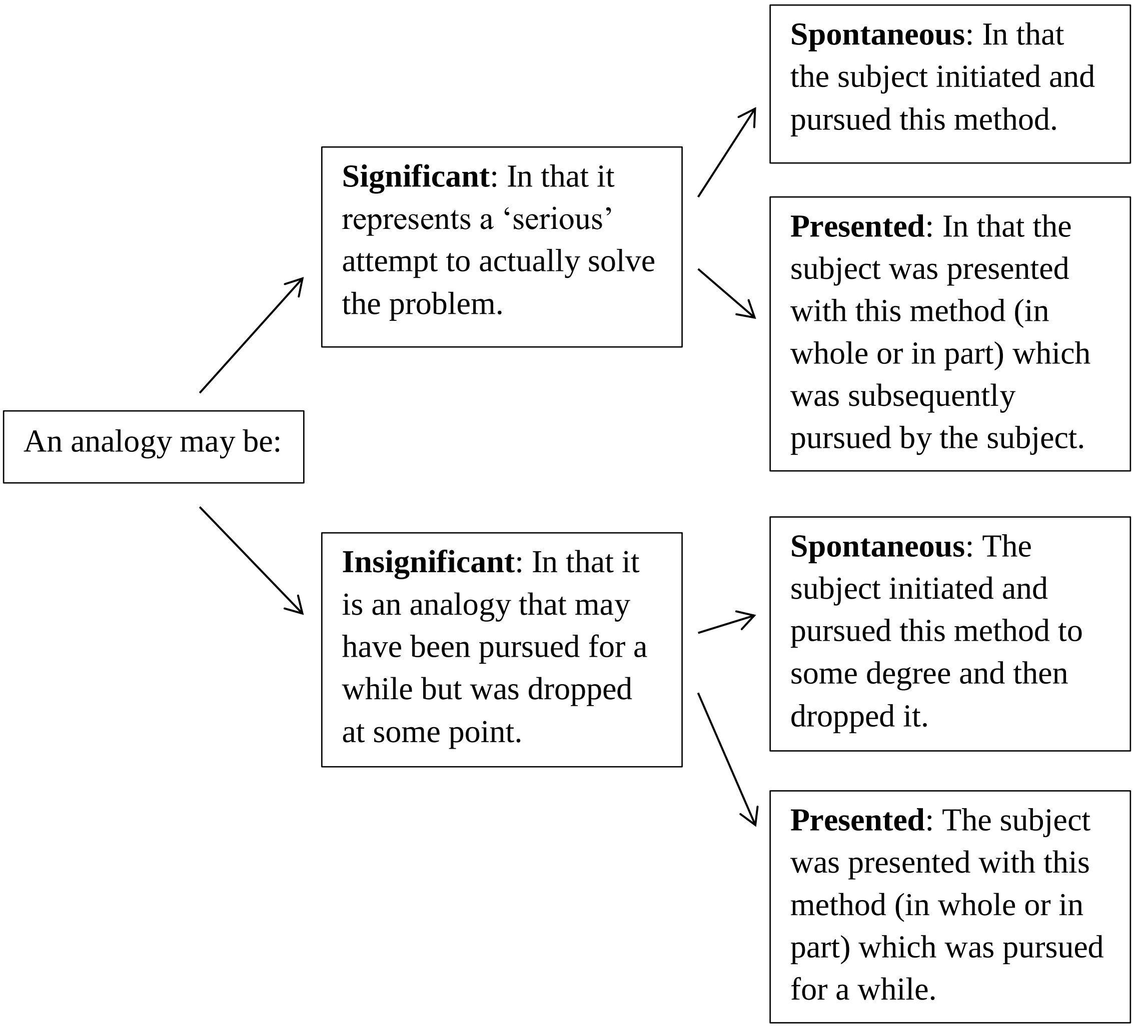


Figure 8: Classification of analogies (Clement, 2009, p. 33-44)

Clement has defined the term ‘spontaneous analogy’ as one in which, when dealing with problem A, the subject, without provocation, refers to another situation, B, where, in B, one or more features which are ordinarily assumed fixed in the original problem situation, A, are different. In other words, the analogous case, B, violates a

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[3] The term, ‘significance,’ for a strategy carries the connotation that other strategies may be ‘insignificant,’ which may not be the case at all, so for the purposes of the present work the term ‘usefulness’ (in whatever the context may be) will be used.

> "fixed feature" of A. The subject will conclude that certain structural or functional relationships may be equivalent in A and B, and will therefore describe the related case B as being at approximately the same level of abstraction as A (Clement, 2009, p. 36).

2.7 Summary

Following the review of pertinent literature in which a model-based view of physics has been discussed, models in teaching and learning and the role of hands-on tasks in conceptual development were reviewed, as well as the concepts in cognitive processes, theory-ladenness, student epistemologies and problem-solving strategies were outlined, the details of the actual study are presented next.

3 Research methodology

3.1 Research design

Research design, according to Creswell (2009, p. 5), has three components, namely: 1) the researcher’s philosophical worldview, 2) the research strategies that are selected, i.e., qualitative, quantitative and/or mixed modes, and 3) the specific research methods that are to be employed, i.e., the type of data collected, the type of analysis, and the interpretation. The research design adopted for this study will be considered from these three points of view and in order to facilitate the discussion the research questions are repeated here.

For the purpose of the present work it is posited that modelling in physics takes place within a particular model-based view of physics - one in which it is proposed that there are five identifiable processes that are required to fully formulate a model in physics, namely the processes of: *particularisation, application, realisation, idealisation* and *approximation*. See Figure 1: A model-based view of physics by Buffler *et al*. (2008). The present research seeks to determine which strategies 1st-year university physics students adopt as they engage in short, hands-on tasks in the laboratory and it is of relevance that the students who are the subjects of the study are being taught in an environment that has adopted a model-based view of physics.

More specifically, the following research questions will be addressed:

1) what strategies do students adopt when required to *particularise* and *apply* physics theory and why do they adopt those strategies?
2) what strategies do students adopt when required to *realise* a physical model as a conceptual model?
3) what strategies do students adopt when required to *idealise* and *approximate* observations they have made of real world phenomena and why do they adopt those strategies?

3.1.1 The worldview adopted for the research

By worldview, or “paradigm” as it is described by Cohen, Manion and Morrison (2011), it is meant “a basic set of beliefs that guide action” (Creswell, 2009, p. 6). In this context, the relevant worldview has been shaped by the discipline of physics, the beliefs of the researcher and his/her supervisors, and past research in the field. Moreover, as indicated by the nature of the research questions, the present work was conducted in a highly ‘discipline specific’, theory-laden environment and as such the data and the interpretation of the research is not independent of the theory that underpins the research (Gall, Gall & Borg, 2007).

Since there has been limited previous research in this specific area, there is no readymade theoretical framework or classification of research strategy to which the researcher could appeal. Therefore the approach adopted for the present work was, as described by Creswell (2007, p. 10), that of a ‘pragmatic worldview’. In this regard the design, methods, techniques and procedures that were chosen for the study were those that it was believed would best meet the needs and purposes of the study, i.e., a worldview that would be driven by intention to address the research questions listed above.

3.1.2 Research strategy selected

In considering the research style to be selected for the present work, the primary consideration was that the research questions address student strategies that could be inferred from the actions of individuals, and their individual construction of meaning. However, the individual action and meaning making was influenced by interaction with other students, and while the interaction within the group during the engagement was not the focus of the study, it was a mechanism through which the individual action and meaning making could be described. In this way the individual student voices were expected to be reflected in the complexity of views within the group. This requirement suggests that a qualitative approach to the research would be appropriate. However, the fact that the research was conducted within a specific, posited, overarching theory (a characterisation that generally calls for a quantitative approach), suggested that an appropriate research strategy may possibly have a ‘mixed’ approach (Creswell, 2009, p.3).

When considering from the point of view of the possible research styles proposed by Cohen, Manion and Morrison (2011), it was suggested that the appropriate style of research could be described as a *case study* in that the purpose of the research question was to capture the complexity and ‘situatedness’ of behaviour in which the focus would be on the individuals in a group setting where the researcher has to apply an interpretive and inferential analysis in a study characterised by a need to find out what can be learned from a specific set of cases (Cohen, Manion & Morrison, 2011. p. 129).

However, given that the interest in this study was in identifying strategies in a particular context, and that that context did not follow any clear definition of a previously identified style of research, a qualitative research design was chosen for this study. Within that broad description, the chosen design may be considered interpretivist in that it is a “study of the immediate and local meanings of social actions for the actors involved” (Gall *et al.*, 2007, p. 31). According to Cohen, Manion & Morrison (2011):

> an interpretivist paradigm rests, in part, on a subjectivist, interactionist, socially constructed ontology and on an epistemology that recognises multiple realities, agentic behaviours and the importance of understanding a situation through the eyes of the participants (p. 116).

Finally, having taken cognisance of the narrowly defined context of the research, no attempt has been made in the research design to eventually be in a position to present the findings as generalizable.

3.1.3 Research methods employed

Since the interest in this study was in student sense-making of their hands-on experiences in the laboratory, the student ‘voice’ was considered to be central for selecting the research methods employed in the study. The motivation for the selection is given below and the detail of each method is presented in the appropriate section later.

3.1.3.1 Motivation for the data collection methods

It was recognised that the strategies that are the focus of the study would have to be inferred from the actions taken by the students as well as the explanations they may give for those actions, and therefore, data were collected by three methods: a) by observation, using video recording of groups of students engaging with the apparatus, b) by written responses of each of the students on a standard answer sheet, and c) by interviews conducted with selected students after they had completed the hands-on tasks.

Although the study interest is in the individual student, observations of groups and the use of worksheets were chosen since these are the normal patterns of learning within the 1st-year lab courses. The worksheets were designed to address the research questions directly, and these written responses were used in two ways: a) to analyse the actions as indicators of individual meaning making, and b) as a stimulus for the individual interviews.

It was believed that these sources of data would indeed provide data that were suited to analysis and triangulation that could provide valid and reliable answers to the research questions.

3.1.3.2 Motivation for using grounded theory analysis to interpret the data

Despite the fact that the imposed model-based view (Buffler *et al.*, 2008) adopted for the present work had set research boundaries - that do not accord with regular grounded theory studies – a grounded theory method was used to analyse the data nevertheless. This is because a grounded theory method allows for the interpretation of complex, multifaceted, behavioural concepts as well as being suited to revealing patterns in interwoven, overlapping issues and themes (Creswell, 2013; Gall, Gall, & Borg, 2007); which was considered appropriate for the analysis in the present work.

It was also recognised that the method of analysis used in grounded theory would meet the needs of the study since this kind of analysis does not merely provide a description or an interpretation of the data, but through a systematic set of procedures the analysis allows for the development of “an inductively derived grounded theory” (Strauss & Corbin, 1990, p. 24). Through well-defined procedures grounded theory analysis seeks to uncover concepts that are supported by the data and then makes statements regarding the relationships among concepts and sets of concepts within a particular context of human interaction (Strauss & Corbin, 1994). Moreover, grounded theory analysis requires that the researcher should infer categories of information embedded in the data and then determine the interrelationship between the identified categories of information. From this process it is expected that the theory that emerges may be articulated in “a narrative statement, a visual picture, or a series of hypotheses or propositions” (Creswell, 2013, p. 85).

Typically, in grounded theory studies, data are gathered from: 1) observations, 2) relevant documentation and 3) interviews (Creswell, 2013, p. 89), which accords with the data collection methods that had already been chosen for the present work. Furthermore, in grounded theory analysis the recorded data is transcribed and then relevant segments[4] are identified for further analysis, and it was recognised that this step would allow for triangulation of these three sources of data.

3.1.3.3 Motivation for the presentation of the findings in two parts

In considering the presentation of the findings, it was decided to do so in two parts. Firstly the presentation is done in what may be described as a ‘thin’ description in that it is a presentation of the findings in such a way as to address the research questions directly, as the questions were posed originally. And secondly, the presentation is done in a way that may be described as a ‘thick’ description in that the researcher has “assigned purpose and intentionality” to the observed actions of the students (Ponterotto, 2006, p. 543) and has provided a description of the nature of the students’ engagement with the hands-on tasks.

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[4] A segment (also described by other grounded theory researchers as a *meaning unit* or an *analysis unit*), is defined as, “a section of the text that contains one item of information and that is comprehensible even if read outside the context in which it is embedded” (Gall *et al.*, 2007, p. 466).

While the question of the nature of the student engagement does not address the research questions directly, it presents the essential elements of findings in an interpretive context from which the reader may be “able to discern whether he or she would have come to the same interpretive conclusions” (Ponterotto, 2006, p. 547).

3.2 Sample and sampling

The unit of study in the present work is the individual student; even though the students worked in groups when they engaged with the hands-on tasks. And while the engagement with the hands-on tasks was part of the curriculum, and therefore students were expected to submit their written reports as part of their coursework, student participation in data collection such as videoing of groups as well agreeing to be interviewed was voluntary.

A total of 79 students had enrolled for the PHY1004W course, the first of a three-year course for physics majors at the University of Cape Town. At the start of the year the student profile of the class was typical for the annual enrolment: of the students, 75% were male and 25% female. 70% had completed South Africa’s National ‘matric’ Examination while the balance had completed Independent Examination Board or A-level (or equivalent) examinations. While the enrolled students are generally proficient in English (the language of instruction), 45% of the students do not speak English as their first language; 25% of the students used an African language as their first language, 10% are Afrikaans speakers and 10% spoke German/Korean/Other home language.

3.3 The study context

In 2006 the Physics Department at the University of Cape Town adopted the textbook, *Matter & Interactions* (M&I) by Chabay and Sherwood as the curriculum guide for its first-year, calculus-based course for physics majors. The relevant course code is PHY1004W. Since its introduction the course has followed the M&I textbook closely and has been delivered by experienced lecturers, well versed in the goals of the M&I curriculum. In this implementation, M&I styled laboratory activities are undertaken as well as a computational physics component which is strongly aligned to goals as set out in the M&I curriculum; see Chabay and Sherwood (2008) as well as Buffler, Pillay, Lubben, and Fearick, (2008).

The modelling of physical systems is a theme repeated throughout the curriculum and in this regard the goals expressly stated by Chabay and Sherwood have been adopted including that it is a requirement that "students themselves (are) to engage in the process of constructing models, including simplifying and idealising messy, complex, real-world systems, making approximations, making simplifying assumptions and estimating quantities" (Chabay & Sherwood, 2004, p. 440).

In 2010 the laboratory component of the PHY1004W course was extended to include short, hands-on physics problem-solving tasks similar in nature to the tasks described in the SCALE-UP studio environment; see Beichner, Chabay & Sherwood (2010). These tasks were referred to as minilabs and it was the specific intention that these hands-on tasks would involve students having to simplify and idealise real-world situations as well as to estimate and approximate physical quantities as they generated a solution to the posed problem.

The PHY1004W course is offered over two semesters with a duration of 24 teaching weeks in total. During this time lectures are offered daily and students have to work through a total of 24 weekly problem sets (WPS1 to WPS24). Students also have to attend 24 three-hour afternoon sessions during which theory tutorials, practical activities and computational tutorials are offered. The details of the course can be seen at the departmental website: http://www.phy.uct.ac.za/physics/courses

The hands-on tasks that are the interventions used in this study were introduced in 2010 and 7 tasks in total were interspersed throughout the year. These were included in the weekly problem set (WPS) in the week during which the relevant section of the applicable physics theory was being covered in lectures. The students were expected to go to the laboratories in their own time where they could freely engage with the apparatus for as long as they liked. The researcher provided assistance to the students where needed on how to use instruments with which they were not familiar, e.g., in the reading of a vernier scale.

From the outset, in order to preserve their anonymity, each student who had registered for the course was designated an 'S' number, i.e., S1 to S79. Of the initial cohort of 79 students, 65 completed the final examination at the end of the academic year. Of those who completed the final exam, 47 had engaged in all of the hands-on tasks and had submitted all of the written answers, and it is these students who make up the study sample, i.e., $N = 47$.

3.4 Data source 1: Observations

The observation data that were collected was that of students engaging with a total of 7 hands-on tasks. These hands-on tasks were presented to the students over the course of the academic year. For the purpose of this study, the phrase 'hands-on task' and the word 'minilab' are used interchangeably.

The term 'minilab' is described by Reif and St. John, as "a brief laboratory exercise which focuses on a single topic (e.g., vector properties of acceleration) or aims to teach a specific skill (e.g., estimating errors)" (Reif & St. John, 1979, p. 951), and according to Etkina and Horton:

> Minilabs are short, relatively inexpensive, mostly qualitative experiments conducted in an unstructured, informal atmosphere. They are designed to help the student master concepts by hands-on experimentation. *ibid*. The important thing about minilabs is that all the planning, performing, and 'making sense' of the experiments is done by the students (Etkina & Horton, 2000, p. 136).

The design, schedule and detailed hands-on questions of the hands-on tasks (minilabs) follow below.

3.4.1 Designing the minilabs

In designing the *minilabs* for this study, the following key requirements were carefully considered in each case:

1) Although the unit of study is the individual student, it was necessary that students should work in groups so that the student interaction could be observed. The

alternative of collecting individual observational data, through talking aloud procedures, was considered but rejected as it would be too time consuming, require considerable training, and conflict with the usual coursework setting.

2) The hands-on tasks had to be chosen to meet the requirement for students to engage in the processes of particularisation, application, realisation, idealisation and approximation; processes which were of relevance to the research questions,
3) The hands-on tasks had to meet the need for students to construct physics models that were appropriate to the physics course for which they had enrolled and the work that they were covering at the time, and
4) The hands-on tasks had to be presented to the students in such a way that the engagement was 'student-directed' as opposed to 'teacher-directed' i.e., students were not to be directed to come up with a 'best model'. "Instead, the students should make a decision on the basis of their own arguments" (Van Driel & Verloop, 2002, p 1265).

3.4.2 Minilab schedule and time taken

As previously noted, the first-year course for physics majors at the University of Cape Town is offered over 24 academic weeks, with a weekly problem set (WPS) being presented to the students each week. During the week in which a minilab question had been included in the WPS, students could engage with the minilab in their own time but they had to submit their written answer to the minilab question along with their solutions to the other problems in the WPS. Students had to submit their minilab answers on the prescribed answer sheet, see Figure 23 and Figure 24 below.

Table 1: Table to show the minilab schedule throughout the academic year

Minilab #	Minilab name	Week #	Section of work
1	Impulse and linear momentum	3	Modern Mechanics
2	Interatomic spring constant	4	Modern Mechanics
3	Conservation of energy	7	Modern Mechanics
4	Conservation of angular momentum	9	Modern Mechanics
5	Static field and polarisation	14	Electricity & Magnetism
6	Crossed magnetic fields	18	Electricity & Magnetism
7	Faraday's Law	22	Electricity & Magnetism

NOTE: Minilab #1 was used as an orientation exercise and consequently the data collected from that minilab was not included in the analysis and findings of the study.

The time taken for the students to engage with the minilab apparatus in the laboratory was typically 25 to 35 minutes but there is no indication as to how much time students may have spent either preparing to do the minilab, or how much time they may have spent writing up their answers afterwards. Most observed students appeared to complete the answer sheet immediately after engaging with the apparatus.

3.4.3 Minilab #1: Impulse and the conservation of linear momentum

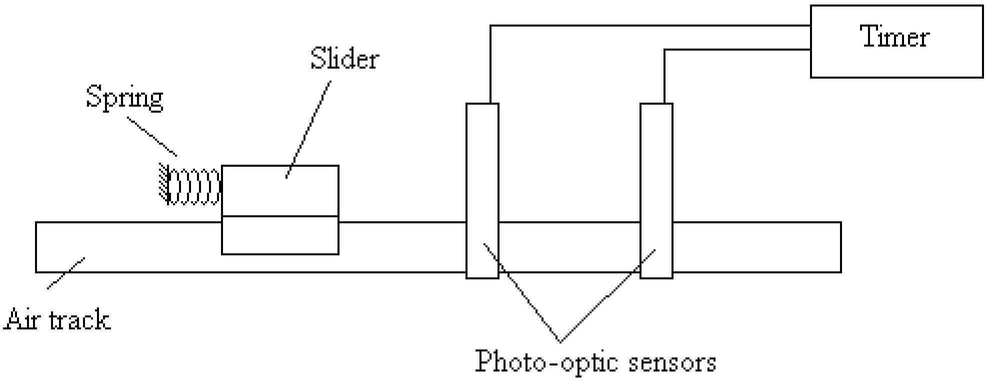
University of Cape Town
Department of Physics
PHY1004W
Weekly Problem Set 3
Question 1
Minilab exercise: 1

<u>Hand in your minilab answer sheet with your WPS solutions.</u>

In this minilab a spring is used to give an impulse to a slider on an air track.

Determine the time (in seconds) that the spring is in contact with the slider.

All the apparatus necessary to perform this experiment is supplied on the mezzanine level of the Course I Laboratory. Find one or two (not 5) other students and go together to the laboratory and proceed with the exercise.



Holding one end of the spring in a fixed position, fully compress the spring by pushing the slider against the free end of the spring; then release the slider.

- The spring has a spring constant of 5.0 N m^{-1}.

Answers are to be provided on the minilab answer sheet.
Write the names of your partners on the answer sheet.

Figure 9: Question for minilab #1, Impulse and linear momentum

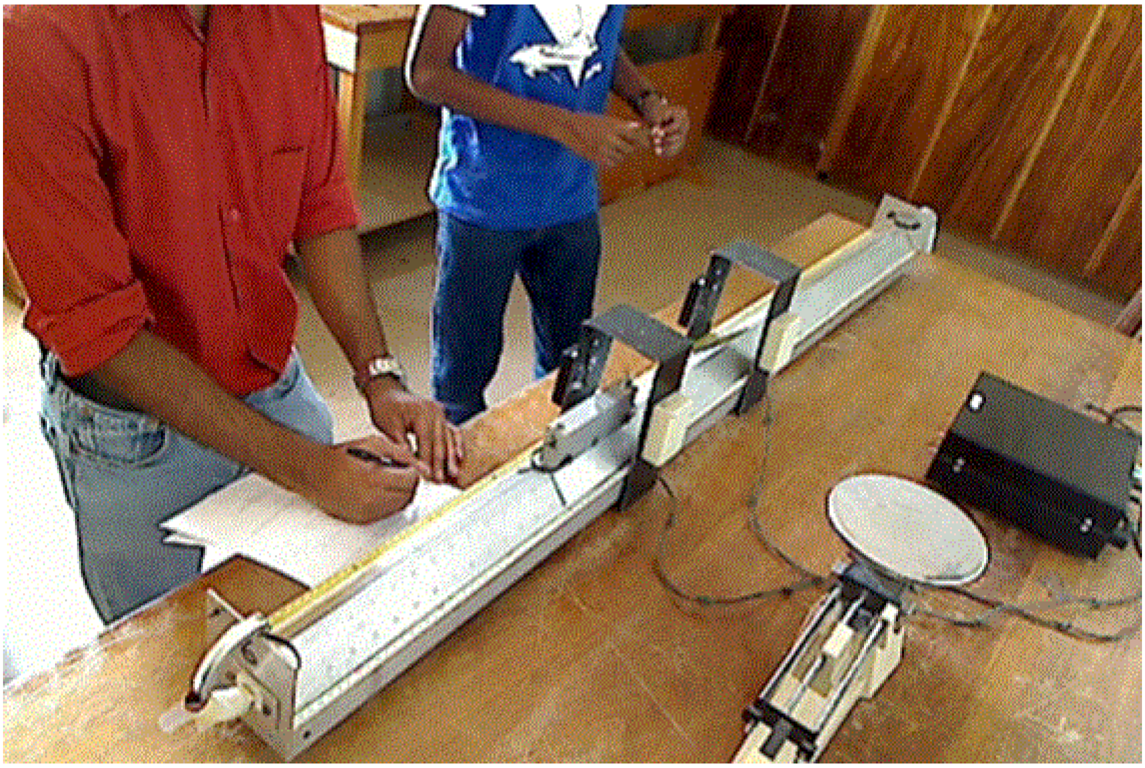


Figure 10: Students engaging in minilab #1, Impulse and linear momentum

Minilab #1 required the application of the principle of conservation of linear momentum as well as the application of Hooke’s Law. It also required the students to identify the components of the apparatus that made up the relevant ‘physical system’.

A slider, on an air-track, was accelerated from rest by a compressed spring and the impulse time of the applied force was to be determined. A set of timing gates made it possible for the students to determine the speed of the slider after it had been accelerated.

It was expected that the students’ particularisation, application and realisation of their model would be guided by a textbook description (p. 61-62) which was very similar to what students had to do. It was however expected that students may have difficulty recognising that they had to use the average force applied by the spring, and not the maximum force, and it was also expected that students would have no difficulty idealising and approximating since the air-track was relatively friction-free.

The time measurements were done electronically, the distance measurement was by means of a metre stick, and the mass was measured by means of a triple beam balance. The only open, unguided question for the students was whether to include the spring (whole or in part) as part of the accelerated physical system.

3.4.4 Minilab #2: Interatomic spring constant

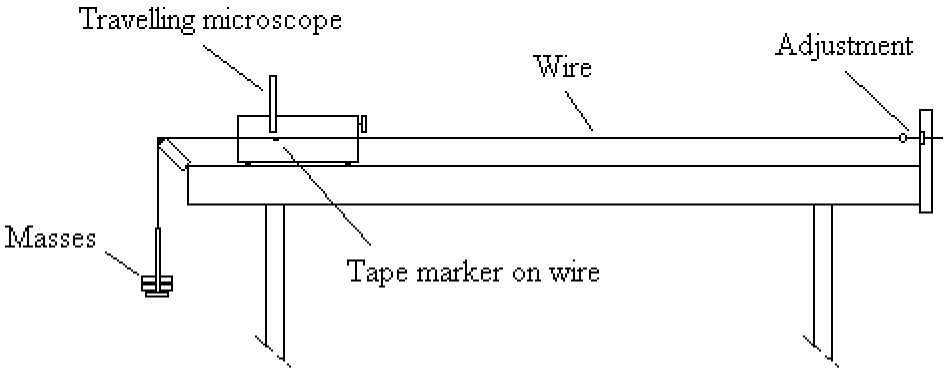
University of Cape Town
Department of Physics
PHY1004W
Weekly Problem Set 4
Question 1
Minilab exercise: 2

Hand in your minilab answer sheet with your WPS solutions.

In this minilab a length of iron wire can be stretched by known force.

Determine a value for the strength (in Newtons per metre) of the interatomic bond between two neighbouring iron atoms.

All the apparatus necessary to perform this experiment is supplied on the mezzanine level of the Course I Laboratory. Find one or two (not 5) other students and go together to the laboratory and proceed with the exercise.



Use a travelling microscope and the masses provided in the lab to measure the extension of a length of iron wire which is placed under tension. From this extension and any other values you require, answer the question posed above.

Answers are to be provided on the minilab answer sheet.
Write the names of your partners on the answer sheet.

Figure 11: Question for minilab #2, Interatomic spring constant

Figure 12: Students engaging in minilab #2, Interatomic spring constant

Minilab #2 required the application of the ball-and-spring model within the micro- and macroscopic views as used in *Matter & Interactions* by Chabay & Sherwood, (2011). A 2 m length of galvanised iron wire, of diameter 0.8 mm, was stretched by applying known loads (0 to 50 N), and the extension of the wire was measured by means of a travelling microscope. The students were ultimately asked to determine interatomic spring constant for the ball-and-spring model.

It was expected that the students' particularisation, application and realisation in this minilab would be guided by a detailed textbook example (p. 145) of a similar experiment, in which a square copper wire is stretched, and which had also been reproduced in the lecture's notes that had been handed out in class. However, it was expected that students may have difficulty learning to use a travelling microscope and to read the vernier scale on the instrument. It was also expected that students' idealisation and approximation of the observed phenomena may have been complicated by the fact that the students were not able to perceive the extension of the wire with the naked eye. A further possible complication was that the microscope inverted the image so that while the actual extension would be to the left of the observer, it appeared through the microscope as though the direction of the extension was to the right.

3.4.5 Minilab #3: Conservation of energy

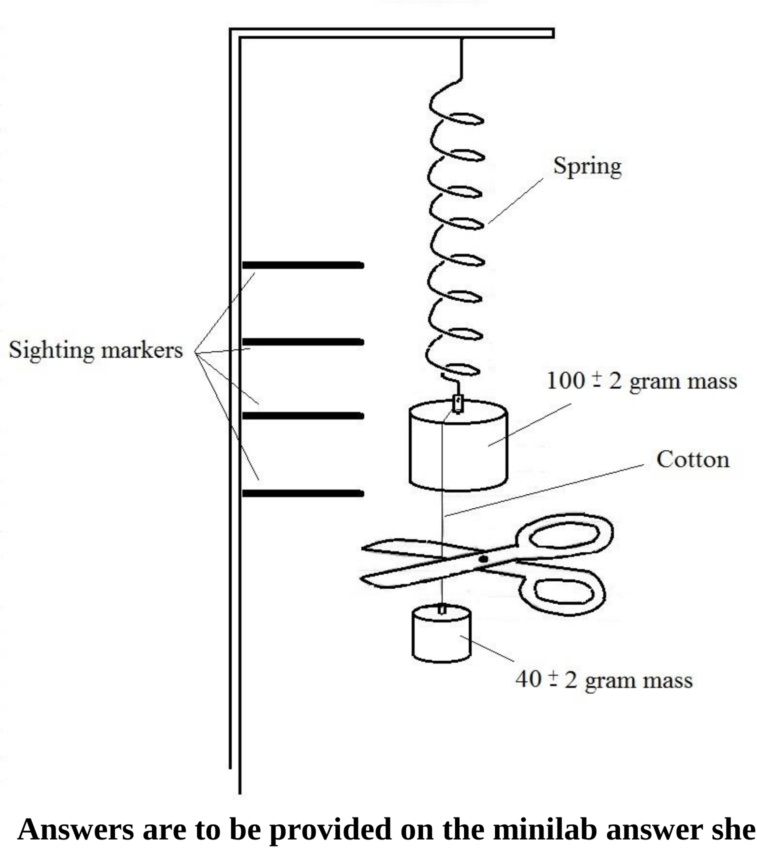
University of Cape Town
Department of Physics
PHY1004W
Weekly Problem Set 7
Question 1
Minilab exercise: 3

<u>Hand in your minilab answer sheet with your WPS solutions.</u>

A mass-spring system, initially at rest, is allowed to oscillate freely after a known mass has been removed from the system.

Determine the amount of energy dissipated from the mass-spring system after it has oscillated for three minutes (from the moment that the 40 gram mass is released), and explain where the dissipated energy may have 'gone'.

All the apparatus necessary to perform this experiment is supplied on the mezzanine level of the Course I Laboratory. Find one or two (not 5) other students and go together to the laboratory and proceed with the exercise.



Answers are to be provided on the minilab answer sheet.
Write the names of your partners on the answer sheet.

Figure 13: Question for minilab #3, Conservation of energy

Figure 14: Students engaging with minilab #3, Conservation of energy

Minilab #3 required the application of the principle of conservation of energy to determine how much energy had dissipated from an oscillating spring/mass system. Students were required to identify the components of the physical system and then apply Hooke's Law to determine the spring constant and thereafter to determine the energy oscillating in the system at t = 0 seconds, and t = 180 seconds.

It was expected that particularisation, application and realisation would be challenging as there was no similar example available in the textbook and by the fact that the majority of the problems being dealt with in lectures, tutorials and WPSs at the time focussed on the potential energy and the kinetic energy in oscillating systems. This classroom focus on $P.E. = K.E.$ was expected to predispose many students to the expectation that the minilab had something to do with determining the kinetic energy of the oscillating mass. It was also expected that approximation of the extension of the spring at t = 180 seconds may have been difficult as there appeared to be no way for the students to determine the maximum extension of the oscillating mass precisely.

3.4.6 Minilab #4: Conservation of angular momentum

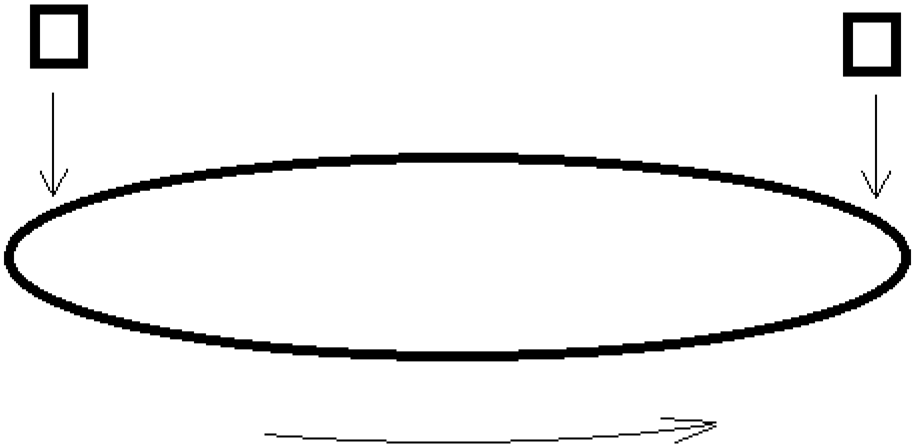
University of Cape Town
Department of Physics
PHY1004W
Weekly Problem Set 9
Question 1
Minilab exercise: 4

Hand in your minilab answer sheet by 10:00 am on 6 May.

A wheel of unknown mass is allowed to turn freely in a horizontal plane.
Two known masses are simultaneously dropped onto the turning wheel close to the rim.

Determine the mass of the wheel.

All the apparatus necessary to perform this experiment is supplied on the mezzanine level of the Course I Laboratory. Find one or two (not 5) other students and go together to the laboratory and proceed with the exercise.



Answers are to be provided on the minilab answer sheet.
Write the names of your partners on the answer sheet.

Figure 15: Question for minilab #4, Conservation of angular momentum

Figure 16: Students engaging with minilab #4, Conservation of angular momentum

Minilab #4 required the application of the principle of angular momentum. Two known masses (1 kg each) are dropped onto a disk (bicycle wheel) that was rotating in a horizontal plane. Stop watches are provided so as to make it possible for the students to determine the change in angular velocity when the masses were dropped onto the disk.

It was expected that particularisation, application and realisation would be guided by three well-described examples set out in the textbook (p. 432-435 and 460) and it was expected that the idealisation of the spinning bicycle wheel may have been complicated by the fact that the wheel had a heavy hub and that the spokes between the inner ring and the outer rim, were covered by a cardboard disk (see Figure 16). It was also expected that approximation may have been made difficult by the fact that the wheel was not friction free and so the number of rotations over which the times were taken had to be optimised. The students also had to work out how to synchronise the operation of the stopwatches. No assistance was given to them in this regard.

3.4.7 Minilab #5: Static electric field and polarisation

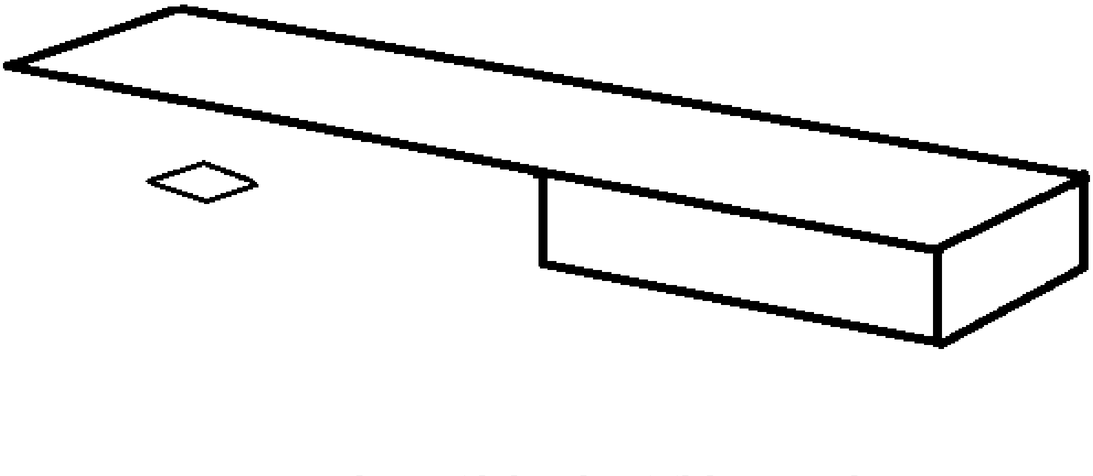
University of Cape Town
Department of Physics
PHY1004W
Weekly Problem Set 14
Question 1
Minilab exercise: 5

Hand in your minilab answer sheet by 10:00 am on 12 August.

A 1 cm x 1 cm piece of 80 g/m^2 white paper is lying on a table. When a charged 30 cm long plastic ruler is held horizontally over, and 2 cm above, the piece of paper, it is noted that the piece of paper is lifted from the table.

Determine the minimum number of electrons that have to be removed from the ruler to make this possible.

All the apparatus necessary to perform this experiment is supplied on the mezzanine level of the Course I Laboratory. Find one or two (not 5) other students and go together to the laboratory and proceed with the exercise.



Answers are to be provided on the minilab answer sheet.
Write the names of your partners on the answer sheet.

Figure 17: Question for minilab #5, Static field and polarisation

Figure 18: Students engaging with minilab #5, Static field and polarisation

Minilab #5 required the application of the concepts of a static electrical field, the polarisation of materials in that field, and the application of Coulomb's Law. A plastic ruler, charged by being rubbing with of piece of wool, when held 2 cm above pieces of 80 g/m^2 paper (each 1 cm x 1 cm) lying on a wooden table top, is able to lift the pieces of paper from the table. Students had to model the observed phenomena in such a way that they could determine the minimum number of electrons that would have to be removed from the ruler in order to make this possible. The students were not required to quantify anything by way of making a measurement, as would be the case in a typical laboratory session with which the students were familiar. Further, a similar demonstration had been done by the lecturer in class.

It was expected that particularisation, application and realisation would present a challenge as there was no single example in the text or in the WPSs that could be used to accommodate all the observations that could be made around the phenomenon. And while the students had been given a great deal of leeway in that they were only asked to determine the 'minimum' number of electrons to be removed, it was expected that approximation of the phenomena may be complicated by the fact that the numbers in the answers were very large and that the answer could vary considerably (i.e., typically 10^{13} to 10^{20}), depending on the modelling choices that were made.

3.4.8 Minilab #6: Crossed magnetic fields

University of Cape Town
Department of Physics
PHY1004W
Weekly Problem Set 18
Question 1
Minilab exercise: 6

Hand in your minilab answer sheet by 10:00 am on 16 Sept.

The compass in a tangential galvanometer is deflected when an unknown current passes through the galvanometer.

Determine the current.

All the apparatus necessary to perform this experiment is supplied on the mezzanine level of the Course I Laboratory. Find one or two (not 5) other students and go together to the laboratory and proceed with the exercise.

The **tangent galvanometer** is a rather romantic instrument and was first described by Claude-Servais-Mathias Pouillet (1790-1868) in 1837. It was originally developed as a sensitive ammeter and was widely used by experimentalists throughout the 19th century. The tangent galvanometer is made up from a compass mounted inside a loop of wire. The wire loop has to be orientated so that the normal of the area enclosed by the loop is perpendicular to the earth's local magnetic field. When there is a current in the coil the compass will deflect one way or the other and the angle of deflection will depend on the ratio of the strengths of the two perpendicular magnetic fields; the field as a result of the current in the coil, and that of the earth. $\tan\phi = B_{coil}/B_{earth}$	

Answers are to be provided on the minilab answer sheet.
Write the names of your partners on the answer sheet.

Figure 19: Question for minilab #6, Crossed magnetic fields

Figure 20: Students engaging with minilab #6, Crossed magnetic fields

Minilab #6 required the vector summing of two perpendicular magnetic fields in the horizontal plane as well as the determination of the magnetic field at the centre of a thin coil. A tangential galvanometer was used to determine the current in a simple circuit which consisted of a power supply and a limiting resistor. No other instruments were supplied and while the students were able to read the voltage setting on the power supply, the value of the limiting resistor was not given.

In preparation for this minilab a description of the earth’s magnetic field was given in class in the week prior to them being presented with this minilab. In that lecture the direction of the earth’s magnetic field (in Cape Town) was described as having an inclination of approximately 45° and that the strength of the horizontal component of earth’s magnetic field (in Cape Town) was approximately 25 µT.

It was expected that particularisation, application and realisation would be guided by two very similar examples in the textbook (p. 724 and 726-727) as well as by a related problem having been done by the lecturer in class. However, the relevant examples in the textbook showed the magnetic field generated by a single loop, and not a thin coil as is the case in the minilab. And it was expected that approximation would be confined to readings taken on a compass and that idealisation would be centred on the visualisation of the components of the resultant magnetic field.

3.4.9 Minilab #7: Faraday's Law

University of Cape Town
Department of Physics
PHY1004W
Weekly Problem Set 22
Question 6
Minilab exercise: 7

Hand in your minilab answer sheet by 10:00 am on 14 Oct.

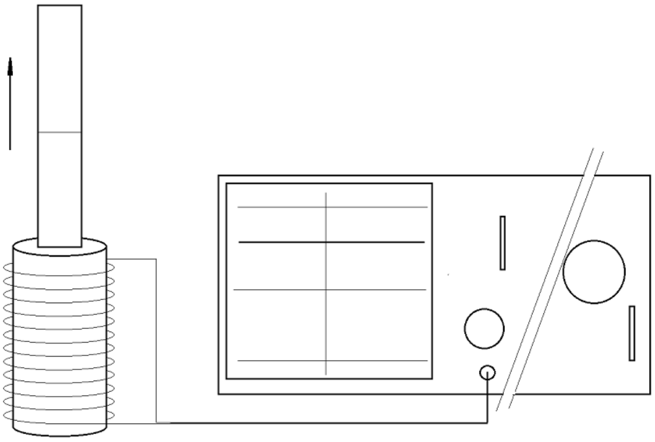
A permanent magnet is pulled out from a solenoid and it is noted that an emf is induced in the solenoid.

Determine the maximum rate of change of the magnetic field (dB_{max}/dt) inside the solenoid when the permanent magnet is being pulled out of the solenoid.

All the apparatus necessary to perform this experiment is supplied on the mezzanine level of the Course I Laboratory. Find one or two (not 5) other students and go together to the laboratory and proceed with the exercise.

In this minilab an oscilloscope will be used to determine the induced voltage.

Note that a typical demonstration of this phenomenon will show how a galvanometer "kicks" one way or the other as the magnet is moved through the coil.



Answers are to be provided on the minilab answer sheet.
Write the names of your partners on the answer sheet.

Figure 21: Question for minilab #7, Faraday's Law

Figure 22: Students engaging with minilab #7, Faraday’s Law

Minilab #7 required the application of Faraday’s Law. A permanent magnet and a solenoid, typical of the apparatus used to demonstrate Faraday’s Law, together with an oscilloscope were used to determine the maximum voltage induced in a coil when a permanent magnet is withdrawn from the coil, by hand, as quickly as possible. In this minilab students also had to use an oscilloscope in a way in which they may not have been familiar.

It was expected that particularisation, application and realisation would be guided by the descriptions and application of Faraday’s Law in the textbook (p. 955) since this is what could be described as a classic experiment, and that the idealisation of the number of turns of a solenoid that needed to be included in the model would play a significant role. To do this idealisation, students were required to visualise the spatial orientation at a cross-section of the magnetic field of a permanent magnet, and then to consider the change in the magnetic flux of each cross-section as the permanent magnet moves away. Furthermore, even though the given value of ‘30 turns/cm’ was printed on the solenoid, it was expected that the approximation of the total number of turns may have been complicated by the fact that while at one end of the solenoid the windings could be seen, the other end was partially obscured by a tape covering, thus requiring the students to approximate the length of the solenoid. (Note: The tape on the windings was not fitted purposefully, but was part of the manufacturing process.)

3.4.10 Group video recordings

It was recognised from the outset that student interaction, while they were engaged with the apparatus, needed to be captured as completely as possible. To this end, a good quality camcorder (Canon Vixia HFS200) was procured and a room leading directly from the area in the laboratory in which the minilab apparatus was set up for recording purposes.

Table 2: Table of video recordings of groups engaging with minilabs

Minilab #	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
1	S5, S30 S38	S10, S15	S51 S72	S6, S12	S20, S23	S3, S18	-
2	S14, S62 S65	S33, S74	S44, S47	S54, S72	S11, S13	-	-
3	S6, S63 S68, S77 S79	S8, S34 S43	S14, S65	S66, S71	S5, S41 S70	-	-
4	S9, S59	S10, S15	S44, S47	-	-	-	-
6	S7, S24 S39, S42	S8, S43 S45	S19, S33	S41, S63 S68, S70	S52, S73	S10, S44 S47	-
7	S4, S20 S22, S23	S5, S70	S7, S24 S63, S77	S13, S39 S42	S14, S41 S62, S65	S17, S53	S33, S36 S74

For each of the minilabs, at least five sets of apparatus were made available to the students and of these, four sets were placed in the open area of the laboratory while one set was placed in the recording room. The door to the recording area was always open and there was no suggestion that the apparatus in the recording room was in any way different from that in the common area. The recording camera was mounted on a tripod and was open for all to see, so there was never any doubt as to what the purpose was for the allocation of the apparatus and the camera in the recording room.

No pre-planning of the recording was done. All of the students had been informed beforehand that research into their engagement with the minilab apparatus was being done and their co-operation was requested. Therefore, when groups of students came to the laboratory to do the minilab they were asked, quite randomly, whether they would allow their engagement with the apparatus to be recorded. Most student groups acceded to this request but not all of them. During the recording the camera was unmanned and one of the things the students were asked to do was to turn off the camera once they had completed their engagement with the apparatus.

3.5 Data source 2: Written responses

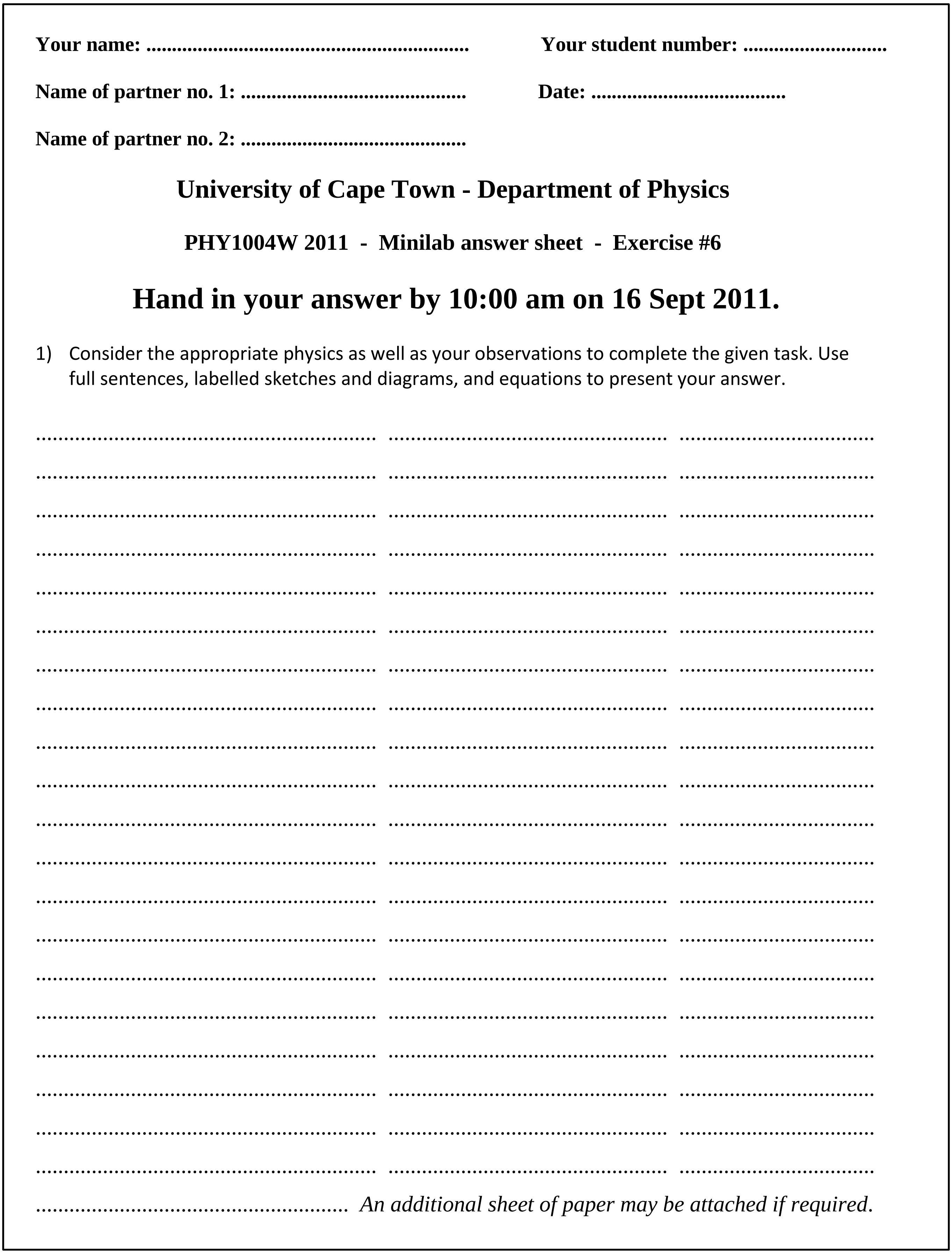
3.5.1 Designing the minilab answer sheet

The prescribed answer sheet can be seen in Figure 23, and Figure 24 below. Given that the intention of the written answer sheet was to elicit students' responses to the processes that were the focus of the research questions, i.e., the responses in regard to particularisation, application, realisation, idealisation and approximation, the justification for the answer sheet sub-sections is as follows:

- In question 1, Figure 23, the phrases 'appropriate physics' and 'observations' were deliberately coupled, as was the instruction to the student to use a multi-representational approach in presenting the answer. This was done in order to elicit students' responses to *all five of the modelling processes*.
- In question 2, Figure 24, the instruction to 'list all the physics theories and equations used' was used in order to elicit students' responses to *particularisation* and *application*.
- In questions 3 and 4, Figure 24, the instruction to list features that were included as well as features that were disregarded was used in order to elicit responses to students' *idealisation*.
- In questions 5 and 6, Figure 24, the instruction to list the quantities evaluated, as well as to comment on the uncertainty in that evaluation, was used in order to elicit students' responses to *approximation*.

3.5.2 Individual written responses – Data source #2

Once the written answer sheets were submitted by the students, each page of the answer sheet was clearly marked with the student's allocated 'S' number, and then the sheets were scanned and collated digitally.



Your name: .... **Your student number:** ....

Name of partner no. 1: .... **Date:** ....

Name of partner no. 2: ....

University of Cape Town - Department of Physics

PHY1004W 2011 - Minilab answer sheet - Exercise #6

Hand in your answer by 10:00 am on 16 Sept 2011.

1) Consider the appropriate physics as well as your observations to complete the given task. Use full sentences, labelled sketches and diagrams, and equations to present your answer.

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.... *An additional sheet of paper may be attached if required.*

Figure 23: Minilab answer sheet; page 1 of 2

2) List all the <u>physics theories and equations</u> you chose to use and give a brief reason why you included each item:

....

....

....

....

3) What were the important <u>features</u> (physical aspects of the apparatus and environment) you included in your answer and give a brief reason why you did so:

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4) Which <u>features</u> (physical aspects of the apparatus and environment) did you **disregard** and give a brief reason why you did so:

....

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....

5) Table of quantities:

List all of the quantities used in the model. Examples: g, time, field strength…	Give the source of the value of the quantity. Examples: Text book, Measured it, Guessed it …	State the value of the quantity used. Examples: 9.81 m s^{-2}, 3.5 ms, 5.0 T …	Rate the uncertainty in the value of the quantity: **Large**, **Medium**, or S**mall**.	Was the influence of the uncertainty in the answer: **Large**, **Medium**, or **Small**
....	....	....	....	....

6) For those values you guessed in 5) above, how did you do so?

....

....

Figure 24: Minilab answer sheet; page 2 of 2

3.6 Data source 3: Individual interviews

At the end of the academic year and after the end-of-year exams, selected students were invited to be interviewed. The student selection was based on the number of times that that student had been recorded, as well as the consistency with which the student had submitted their written responses. The way in which the student may have answered the minilab questions was not a selection criterion.

Table 3: Table showing students interviewed and where observed

Student	Minilab #	Minilab #	Minilab #
S4	7	-	-
S7	6	7	-
S8	3	6	-
S10	1	4	6
S13	2	7	-
S14	2	3	7
S16	-	-	-
S19	6	-	-
S20	1	7	-
S22	7	-	-
S23	7	-	-
S24	6	7	-
S33	2	7	-
S36	7	-	-
S39	6	7	-
S41	3	6	7
S42	6	7	-
S44	2	4	6
S45	6	-	-
S54	-	-	-
S59	4	-	-
S63	3	6	7
S66	3	-	-
S70	3	6	7
S74	2	7	-

A total of 25 interviews was conducted. Each interview was recorded with the student’s permission, with the video camera in full view of the student and the interviewer. Of the 25 interviews, 21 were conducted by the researcher and 4 by one of the co-supervisors of this study. Each interview lasted between 30 and 45 minutes. The interview process (in italics) and the questions (in bold) were as follows:

Introduction

1) *(Interviewer) Confirm that permission has been given to record the interview.*
2) *Assure the student that the interview has no bearing on the outcome of the course.*
3) *Explain that:*
    - *"When doing the minilab you would have developed a strategy to tackle the problem and we are interested in*
        - *what that strategy was and how that strategy may have changed,*
        - *and what may have prompted the change."*
4) *Assure the student that there are no right or wrong answers to the questions.*

Questions

Introductory question

What did you find engaging about the minilabs?
(*prompt a response if required*)

Video response questions (where there is one):

Please look at the video clip XXX. (*Show clip.*)
Could you tell me about… (the situation)?
(*prompt a response if required*)

(*Look for* ***strategy***) e.g., **I am interested in…**?
e.g., **Could you expand on…**?
(*Look for* ***resource***) e.g., **To what/whom did you turn for help…** ?
(*prompt why*)
(*Look for* ***decision***) e.g., **So you decided…**?
(*prompt why*)

Written response questions: (Repeat the above 2x or 3x as required.)

Please look at your written response to YYY minilab where you wrote…,
(draw attention to a response - give them time to look at it.)
Could you tell me about… (the situation)?
(*prompt a response if required*)

(*Look for* ***strategy***) e.g., **I am interested in …** ?
e.g., **Could you expand on…**?
(*Look for* ***resource***) e.g., **To what/whom did you turn for help…** ?
(*prompt why*)
(*Look for* ***decision***) e.g., **So you decided…**? (*prompt why*)

5) *Tell the student that the following questions are of a more general nature.*

6) *Remind the student that there isn't a right or a wrong in any of their replies.*

Strategy questions:

You have told me something of the strategies you adopted in the examples we have discussed, could you tell me - in general - how your plan for doing the minilabs may have developed from the start of the year compared to how you approached the task in the end? (*prompt a response if required*)
e.g., **Could you expand on…**?

Can you think of any examples where - while you were doing the minilab - you had to change your plan while you were doing the minilab?
(*prompt an example*)
What do you think prompted that change in plan?
(*prompt a response if required*)
In looking back on it, would you adopt a different approach?
(*prompt why*)

Modelling question:

In the PHY1004 course you have been told about modelling, what do you think modelling is all about? (*prompt a response if required*)
e.g., **Could you expand on…**?

Concluding question:

If you were able to tell next year's students how they should approach these minilabs, what would you say to them? (*prompt a response if required*)

Is there anything you would like to ask me about the minilabs?

7) *Thank student for making the time for the interview.*

End of interview

3.7 Data analysis

In the following section, methods pertaining to grounded theory analysis that were used in this analysis are discussed, then an overview of the process of the analysis is given, which is followed by the detailed description of the 3-stage analysis.

3.7.1 Methods pertaining to grounded theory analysis

Terms and methods relative to the analysis used in this study are listed here:

i) Segments

A segment (also described by other grounded theory researchers as a *meaning unit* or an *analysis unit*), is defined as, “a section of the text that contains one item of information and that is comprehensible even if read outside the context in which it is embedded” (Gall *et al*., 2007, p. 466).

ii) Constant comparison and emergent categories

Constant comparison is an iterative process in which identified segments are coded and collated in categories (also described as *themes*), where a category is defined as “a broad unit of information that consists of several codes aggregated to form a common idea” (Creswell, 2013, p. 186). These categories may be collated once again to form sets of categories from which there may emerge broader ideas (sub-categories) that form the evidence of processes, actions or interactions that allows for the eventual interpretation of the data and the presentation of the findings (Creswell, 2013, p. 187).

iii) Saturation

The number of iterations made during the process of constant comparison depends on how quickly the emergent categories become saturated. “Theoretical saturation occurs when no new data (information) are emerging relevant to an established coding category, no additional categories appear to be necessary to account for the phenomena of interest, and the relationships among the categories appear to be well established” (Gall *et al*., 2007, p. 469). A state of saturation will have been reached when the proposed theory is elaborated in all of its complexity, but there is a caution, the “final theory (that emerges) is limited to those categories, their properties and dimensions, and statements of relationships that exist in the actual data collected – not what (the researcher may) think might be out there but haven’t come across” (Strauss & Corbin, 1990, p.112).

iv) Open, axial and selective coding

It is customary in grounded theory analysis to refer to the type of coding that may be used at the different stages of the analysis as open, axial and selective coding, although, as pointed out by Strauss and Corbin (1990, p. 58), these processes are tightly integrated and it is not always possible to delineate the actual coding in these terms. Open coding refers to “examining each line of data and then defining actions or events within it”, axial coding refers to the type of coding that “is aimed at making connections between a category and its subcategories”, and selective coding refers to using “initial codes that reappear frequently” (Charmaz, 2000, p. 515-516).

At each stage of the analysis as described herein, the principles of grounded theory analysis were applied as closely to the intention of the method as possible, i.e., data were segmented, examined repeatedly and through constant comparison, categories were developed and grouped until saturation was reached. However the limitations in the application of a purely grounded theory analysis were recognised and these are discussed in the section dealing with the validity and reliability of the study.

3.7.2 Overview of the 3-stage data analysis used in this study

Data were obtained from three sources - group observations, written answers and interviews – and the analysis of those data was done as a 3-stage process as depicted in Figure 25.

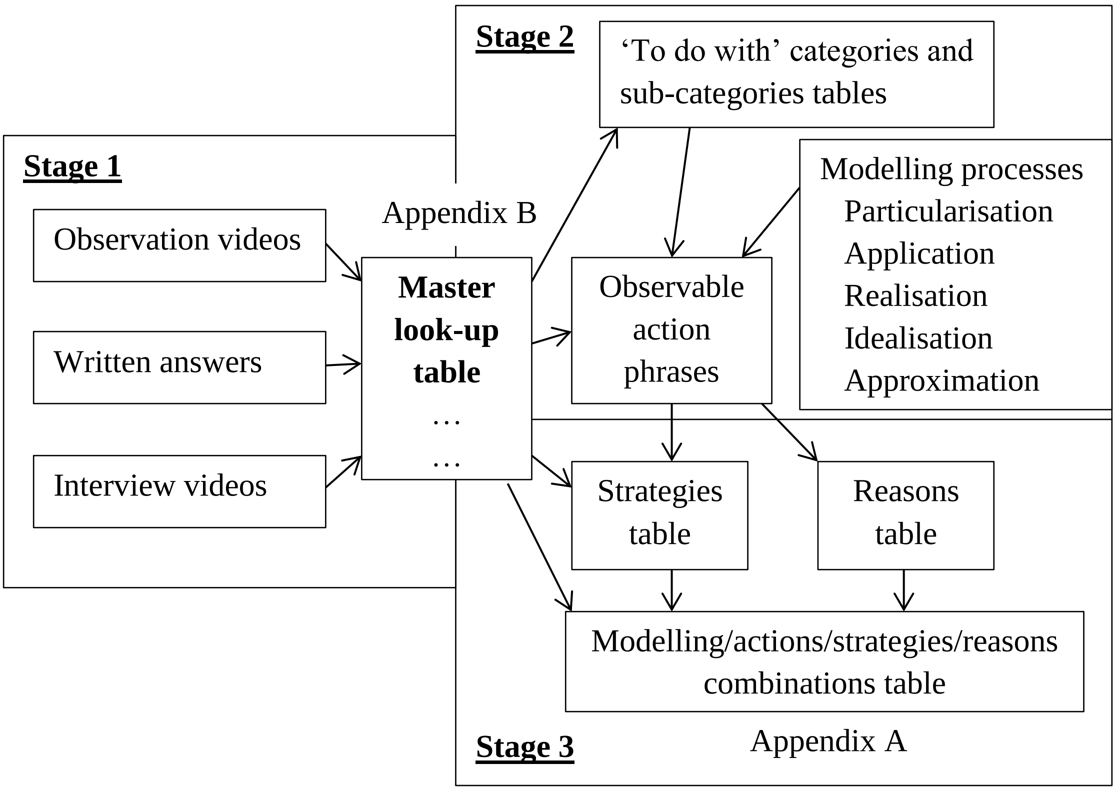

Figure 25: Diagram to show the process of data analysis

1) In the first stage the data were segmented (defined above) and contextualising memos were added so that the segments from each of the three sources could be treated as a consolidated set of data. The segments were collated in a Master look-up table.
2) In the second stage the method of constant comparison was used to identify the observable actions in which the students engaged. These actions were categorised as observable action phrases and were linked to the modelling processes that frame the research questions.
3) In the third stage the method of constant comparison was used to infer, from the action phrases and the context, the underlying strategies and the reasons for adopting those strategies.

In the design of the analysis architecture and the documentation, at least six passes were made through the data during which time various methods were devised and tested. Finally, it was found that a set of simple EXCEL© flat files would provide the most flexible and open method to code and collate the categories as they emerged and consequently the EXCEL files (tables) that can be seen in Figure 25 were used in the final analysis.

Pivotal to the analysis is the Master look-up table which is a collation of the coded data segments taken from all three data sources and its central role in the analysis can be seen in Figure 25. Of significance is that although the segments from each of the three data sources were combined into a consolidated look-up resource, the originating source and context within which each segment of data was collected was not lost. The segment source was captured within the coding and its relationship with the other two sources was considered throughout, even when secondary and tertiary stage coding took place.

3.7.3 First stage: Transcribing, segmenting, and adding a researcher’s memo

This stage is characterised by an open coding process in that it was designed to provide a consolidated set of data by transcribing all of the video recorded material – the observed as well as interview data - as well as extracting relevant units of information from the written data. Aspects relating to the validity and reliability of the study in regard to this coding have been addressed in the section dealing with the quality assurance plan discussed at the end of this chapter.

The goal of this stage was to consolidate the entire store of raw data as ‘segments’ that could be viewed as surrogate data for further analysis in stages 2 and 3 and consequently there was no requirement to consider any categories of segment as yet. In this stage of the analysis, the written submissions were read and the video recorded material was watched a number of times. The intention when doing these passes through material was to become “immersed” in the data and to look for features and multiple forms of evidence (which could be cross-referenced) that would support what could subsequently be described as the “larger thoughts” (Creswell, 2013, p. 184).

Examples of segments that had been coded during the first stage of the analysis are shown in Table 4, Table 5 and Table 6 below. These three tables - all extracts from Table 36, the Master look-up table - are reproduced here for the purpose of illustrating how the segmenting of the data from each of the three sources was done. Each segment was given a unique number, in the left-most column, and all cross-referencing within the data is done in terms of this segment #. The case number refers to the observed video recording, in Table 2, while the location number, location #, refers to the time-stamp on the recorded video or the relevant question in the written sheet.

The example in Table 4 shows the transcript and researcher's memo of a selection of segments from the video recording (source #1) that describes part of a discussion between students S9 and S59. In this example, the students were grappling with the problem of how many rotations they should time before and after dropping the masses onto the rotating wheel in minilab #4.

Table 4: Example of data segments from observed data (video recordings)

Segment #	Source	Minilab #	Case #	location #	Student S#	***Note on context (in italics)* and "Transcript" or written response**	**Researcher's memo**
436	1	4	1	14:35	9	*S9 appears to be confident of what has to be done next, Ref Inc #376*. How many loops (shows rotations with her finger) do you want to take before you put the masses on?	S9 appears to be using the "checking" strategy of engagement in that the number of turns had been raised three times prior to this
437	1	4	1	14:38	59	*S59 responding to S9 asking how many rotations they should time before adding the masses to the wheel (ref 436)*. I think three	There is no indication as to what prompted the number of three turns, although the earlier discussion about timing one or more turns would have paved the way for the decision
438	1	4	1	14:50	9	*S9 confidently starts taking readings without discussing the details with S59. S59 drops the masses on the wheel when told to do so. S9 continues to determine the times taken.* Put the masses on (S9 has set the wheel turning and has started the stopwatch)	S9 appears to be in control of the process
439	1	4	1	15:15	59	*S59 has noted that the masses fell with a clatter and has suggested improving the experiment*. Ok, let's do it again, from a lower height	S59 did not enquire as to whether the timing process was successful or not.
440	1	4	1	15:25	9	*S9 has decided to take the time for ten turns before dropping the masses and then the time for ten turns after dropping the masses*. I am going to take readings for ten turns	By now it should have become apparent to the students that the wheel slows down and that it will do so markedly over a period required for ten turns
441	1	4	1	15:30	59	*S59 appears to be in agreement at first but later appears to query the need for timing a larger number of rotations*. Ok…, ten readings?	At one stage they were only going to measure the time for one rotation. (*Ref* 393)

442	1	4	1	15:35	9	*S9 does not give a full explanation but S59 agrees to the change, Ref Inc #441*. (Using ten readings) we will get a better average	**EXAMPLE of IDEALISING FRICTION**: S9 appears to be increasing the number of measured turns in order to reduce the uncertainty, but she has not considered the problem of the wheel slowing down
443	1	4	1	15:36	59	*S9 spins the wheel, starts the stopwatch, counts ten revolutions, S59 drops the masses and they time the rotation for a further ten revolutions*. Ok	

The example in Table 5 shows the transcript and researcher's memo of a selection of segments that describes part of the written answer sheet (source #2) by student S9. The location # shows that the segments are derived from the student's answer to question 1, which was the general answer to the minilab question. In this case it was noted in the observed data that the students first spoke about timing one turn (ref. 393), then they were going to time three turns (ref. 437), and finally they actually timed ten turns (ref. 442); yet, in their written work, they used the readings for four turns (ref. 470); so cross references were made in the researcher's memo accordingly.

Table 5: Example of data segments from written data (prescribed answer sheets)

Segment #	Source	Minilab #	Case #	location #	Student S#	***Note on context (in italics)* and "Transcript" or written response**	**Researcher's memo**
469	2	4	1	1	9	S9 included a drawing of the physics system, but did not include a vector diagram	
470	2	4	1	1	9	S9 used four of the ten readings taken during observation in the calculation of the result	**EXAMPLE of USING OTHER DATA:** S9 had taken 10 times before and ten after but only used four before and four after in her calculations. i.e. data appears to have been used selectively
471	2	4	1	1	9	S9 did not use the radius of rotation of the masses, in her answer, that she had recorded in the observation	**EXAMPLE of USING OTHER DATA**: S9 had measured 14.5 cm (ref 462) but used 20.0 cm in her answer *Selective use of the data taken*
472	2	4	1	4	9	S9 We took the rotational axle to be frictionless 'because the friction was small enough to be neglected"	This is *in contradiction to the observation made* when taking the readings (ref 464)

The example in Table 6 shows the transcript and researcher's memo of a selection of segments that describes part of the interview response (source #3) by student S59. It had been noted that students S9 and S59 worked very closely together - their written submissions were very similar, sometimes using exactly the same words - though student S9 appeared generally to take the lead whenever they were observed in their engagement with the minilabs, so a cross reference was included to this effect.

Before proceeding with the interview discussion reproduced in Table 6, student S59 and the interviewer had watched the observed material together, part of which is reproduced in Table 4, and had reviewed the student’s written response, which was materially the same as that reproduced in Table 5.

Table 6: Example of data segments from interview data

Segment #	Source	Minilab #	Case #	location #	Student S#	***Note on context (in italics)* and "Transcript" or written response**	**Researcher's memo**
481	3	4	1	05:30	59	*S59 responding to the question as to how they solved the problem of how to take the times*. She (S9) started using her cell phone (to take times) because the timers (stopwatches) were really confusing us.	
482	3	4	1	09:16	59	*S59 in reaction to watching the observed video recorded Segment where S9 says, "assume this (the wheel) to be frictionless" (ref 426)*. I was really struggling with that in my mind because I thought the wheel, 'cos it was assumed to be frictionless (and we saw) it was not absolutely frictionless, it would actually slow down and then if you put the masses on top it would slow even more.	**EXAMPLE of IGNORING AN OBSERVATION**: It was still not clear at this stage as to whether S59 ascribed the slowing down after the weights had been added to friction or to a change in the angular momentum of the added masses
483	3	4	1	09:43	59	*S59 responding to the prompt that they did find that the wheel slowed down and that times for fewer revolutions had to be taken*. (We had to take time for) two or three turns and then put the masses on straight away and then… (shows hand rotations)	**EXAMPLE of MAKING UP DATA**: Although S59 has reported in the interview that fewer turns were necessary, that is not what they were observed to do. The use of fewer turns appears to have been decided upon at the write-up stage. *Ref Inc* #444 & 455 where 10 revolutions were timed
484	3	4	1	09:50	59	*S59 reflecting on how the two members of their group decided on how many rotations of the wheel to time*. I think she (S9) wanted to leave it to spin like 10 times; I was struggling with that in my mind a bit.	S59 reflecting on the fact that there was some doubt as to how many turns to time
485	3	4	1	10:20	59	*S59 responding to the question as to whether her regular minilab partner, S9, would typically take charge of what the two of them were doing*. In the beginning yes but nowadays she does listen to me	There was no indication from other data sources that S9 did not continue to "be in charge"

It was noted in this example that student S59 had referred to the expectation that the wheel would be frictionless and that the two students had observed it not to be so. It was also noted that both of these students reported in their written submission that they took, “the rotational axle to be frictionless 'because the friction was small enough to be neglected’.” Since student S59 twice used the phrase, “I was struggling with that in my mind,” the comment highlighted a comment in the researcher’s note (ref. 482), there is a suggestion that student S59 may have been perplexed not only by the application of the physics principle that the minilab was designed to explore, but also by the procedural and observational difficulties encountered at the time of the engagement with the minilab apparatus.

By the end of stage 1, a total of 1,314 segments had been captured and for the support of the findings and discussion, all of these segments were considered. However, as the analysis progressed, it soon became clear that coding such a large number of segments was not necessary as saturation of the categories that were derived in stages two and three was reached well before that point. So, for the final stage of the analysis, in which the distribution of the identified strategies was sought, it was decided to truncate the Master look-up table to a total of 500 segments. No special criteria were used in the truncation other than it was assured that segments 1 – 500 were fully representative of the full set of data; this was so because the data from the three sources had been segmented in parallel.

3.7.4 Second stage: Identifying action phrases and linking to modelling processes

The second stage of the analysis is characterised by an axial and selective coding process in that this stage was designed ultimately to link the coded segments in the Master look-up table to the modelling processes that underpin the model-based framework within which the study was done. As depicted in Figure 25, the coding in this stage began with the coded segments captured in the Master look-up table, an extract of which is shown in Appendix B, Table 36. Then, through a ‘zig-zag’ process of constant comparison, action categories emerged which are linked to the pre-defined modelling processes.

The first step in this stage was to consider each segment in the Master look-up table with respect to the question, “*With what* (action or modelling) *is the student engaged here*?” The expectation being that the answer to this question would have the form, “(this segment has) *to do with* (progressive verb).” The answers to the question, “with what aspect of the student’s engagement, regarding actions and/or procedures, is this segment concerned?” are listed in Table 7. In drawing up this primary list of ‘to do with’ categories, no limit was placed on the number of categories that could be identified and no *a priori* names to categories were imposed. Subsequently, a total of 73 ‘to do with’ categories were listed and each segment in the Master look-up table was coded accordingly. Since each of the segments has a unique segment number, there was no possibility of double coding.

The second step in this stage of the analysis was to consider the full list of the ‘to do with’ answers and to re-categorise each of these into sub-categories as appropriate. Five primary ‘to do with’ sub-categories were identified, namely categories that have ‘to do with’: 1) student interaction, 2) engaging with physics theory, 3) engaging with the apparatus, 4) producing the written submission, and 5) referring to resources.

Where appropriate the sub-categories were sub-divided once again and the table showing the emerging ‘to do with’ sub-categories, A, as well as their respective sub-divisions, B, are shown in Table 8. Those segments that did not appear to make a contribution to the emergence of a ‘to do with’ detailed explanation were not coded.

Table 7: Sorted ‘to do with’ (progressive verb) categories

Key: code # is the numbered ‘to do with’ category, 1 to 73; codes ‘A’ & ‘B’ relate to the sub-category coding

#	**‘To do with’ (progressive verb) and topic**	A	B	**‘To do with’ sub-categories**
68	… explaining what the student understands by what is meant by "modelling"	1	0	Non-specific
53	… using the minilabs to concretise (clarify) the physics learned in lectures	1	0	Non-specific
55	… (one student in the group) taking the lead in performing the group task	1	0	Non-specific - group dynamics
59	… (a student) disengaging from the group during the minilab	1	0	Non-specific - group dynamics
5	… finding out what steps to take when "stuck"; (ref 9, 20, 25)	1	1	Choosing a strategy - Procedure
9	… following step-by-step instructions (ref 22,)	1	1	Choosing a strategy - Procedure
14	… carrying out a pre-planned action	1	1	Choosing a strategy - Procedure
19	… broadly looking for what is to be achieved - top level (ref 20, 25)	1	1	Choosing a strategy - Procedure
20	… itemising what has to be done procedurally (ref 19) a, b, c,…	1	1	Choosing a strategy - Procedure
22	… following instructions on the task instruction sheet (ref 9)	1	1	Choosing a strategy - Procedure
26	… stating by way of focus/confirmation what the final goal is (ref 5, 9 20)	1	1	Choosing a strategy - Procedure
48	… having a plan (strategy) to follow at the start. i.e., beforehand.	1	1	Choosing a strategy - Procedure
61	… making an obvious but unintentional mistake in procedure/reading/etc.	1	1	Choosing a strategy - Procedure
23	… visualising, spatially, what is to be done - usually with hand gestures	1	2	Explaining - Convincing
37	… dealing with confusion by conflicting suggestions/question; particularly in larger groups	1	2	Explaining - Convincing
47	… dealing with cognitive dissonance, where the student appears puzzled or confused	1	2	Explaining - Convincing
58	… seeking clarification as what is going on, what others are doing, seeking to engage	1	2	Explaining - Convincing
63	… rationalising/reasoning about a procedure	1	2	Explaining - Convincing
15	… stating disagreement with one or more students in a group	1	3	Expressing disagreement
64	… declaring being confused or puzzled	1	3	Expressing confusion
16	… resolving a disagreement or acceding to some point, or agreeing with a suggestion/view	1	4	Expressing agreement
6	… reflecting on feasibility of a calculated or a measured value	1	5	Reflecting on correctness
31	… anticipating the outcome of an action	1	5	Reflecting on correctness

32	… declaring a result (a reading or a calculation) to get confirmation	1	5	Reflecting on correctness
35	… checking whether a calculated answer is correct	1	5	Reflecting on correctness
1	… finding or selecting a formula	2	1	Engaging with theory - Selecting
7	… verifying that the chosen formula is correct and/or correctly applied	2	1	Engaging with theory - Selecting
21	… randomly picking on **a variable** a-contextually (from an equation) e.g. "What is R?"	2	1	Engaging with theory - Selecting
33	… seeking to identify the variable represented by a given symbol in a formula (see 12)	2	1	Engaging with theory - Selecting
34	… declaring what/which formula to use (perhaps for confirmation)	2	1	Engaging with theory - Selecting
36	… looking for, or not, a physics principle or a more complicated solution rather than a formula	2	1	Engaging with theory - Selecting
40	... selecting an equation that has another embedded it, e.g., Mu = NIA	2	1	Engaging with theory - Selecting
70	… looking for and or finding an applicable physics concept	2	1	Engaging with theory - Selecting
12	… looking for physical attributes to 'fill in' formula variables. e.g. "what is R?" (see 33)	2	2	Engaging with theory - Using
24	… comparing/connecting the task with WPS	2	2	Engaging with theory - Using
25	… itemising variable is a formula as a checklist (ref 9, 20) a, b, c,…	2	2	Engaging with theory - Using
38	… comparing/connecting with lectures or a pre-minilab talk by researcher	2	2	Engaging with theory - Using
39	… looking for a reference of any sort i.e. textbook, internet, notes, etc.	2	2	Engaging with theory - Using
42	… demonstrating a broader & coherent grasp of the physics in question	2	2	Engaging with theory - Using
51	… considering him/herself (student) to be, or not to be, a "hands-on" person	2	2	Engaging with theory - Using
54	… copying or "stumbling across" a solution as opposed to looking for and finding it directly	2	2	Engaging with theory - Using
71	… overlooking a relevant variable because it is not in the formula	2	2	Engaging with theory - Using
72	… providing an incorrect answer due to a misunderstanding of the relevant physics	2	2	Engaging with theory - Using
3	… finding out how to use instrument	3	0	Engaging with apparatus - General
10	… optimising a task e.g. easier to perform by changing a position or setting a marker (ref 18)	3	0	Engaging with apparatus - General
17	… taking more than one reading (ref 8) (to do with procedure)	3	0	Engaging with apparatus - General
18	… making a task easier by setting the equipment to be able to read from zero (ref 10)	3	0	Engaging with apparatus - General
28	… randomly drawing attention to **an object or an observation** a-contextually	3	0	Engaging with apparatus - General
30	… drawing attention to a **practical problem/difficulty** to be overcome	3	0	Engaging with apparatus - General
41	... physically removing possible and identified extraneous influences on the apparatus	3	0	Engaging with apparatus - General

60	… proposing a course of action relating to an observation (may be classified as a procedure)	3	0	Engaging with apparatus - General
66	… describing an observed phenomenon to group members or to interviewer	3	0	Engaging with apparatus - General
67	… reporting on having seen something when in fact they had not	3	0	Engaging with apparatus - General
29	… idealising the physical property of an object	3	1	Engaging with apparatus - Idealise
50	… considering friction	3	1	Engaging with apparatus - Idealise
2	… reading a scale	3	2	Engaging with apparatus – Approx
8	… repeating a procedure/reading to reduce, by inference, uncertainty (ref 17)	3	2	Engaging with apparatus – Approx
27	… reading or interpreting tabulated information/instructions	3	2	Engaging with apparatus – Approx
43	… focussing on obtaining the value of a variable in a given formula	3	2	Engaging with apparatus – Approx
69	… recording a reading	3	2	Engaging with apparatus – Approx
73	… having a sense of the orders of magnitude	3	2	Engaging with apparatus – Approx
11	… reducing the uncertainty of a reading by using zero	3	3	Engaging with apparatus – Uncert.
56	… reducing the uncertainty because the scale of the instrument has lots of markings	3	3	Engaging with apparatus – Uncert.
62	… estimating the uncertainty in a reading	3	3	Engaging with apparatus – Uncert.
13	… producing a multi-representational output of any sort - sketches, graphs, diagrams, etc.	4	0	Writing submission - Representing
4	… adopting a 'null' solution when not knowing what to do with a recognised problem	4	1	Writing submission - Selecting
57	… listing important features (in q3 of the written work) that were not used in the answer	4	1	Writing submission – Selecting
65	… selectively using data (where reported data is not the same as observed)	4	1	Writing submission – Selecting
44	… using the text book as a resource	5	0	Referring to a resource
45	… using self-generated notes as a resource	5	0	Referring to a resource
46	… using the internet as a resource	5	0	Referring to a resource
49	… using other members of the group or other students as a resource	5	0	Referring to a resource
52	… using notes issued in class as a resource	5	0	Referring to a resource

Table 8: Final ‘To do with’ sub-categories and sub-divisions

A	B	**‘To do with’ sub-categories**
0	0	Non-specific
0	1	Non-specific - group dynamics
1	1	Choosing a strategy - Procedure
1	2	Explaining - Convincing
1	3	Expressing confusion
1	4	Expressing agreement
1	5	Reflecting on correctness
2	1	Engaging with theory - Selecting
2	2	Engaging with theory - Using
3	0	Engaging with apparatus - General
3	1	Engaging with apparatus – Idealise
3	2	Engaging with apparatus - Approximate
3	3	Engaging with apparatus - Uncertainty
4	0	Writing the submission - Representing
4	1	Writing the submission - Selecting
5	0	Referring to a resource

The third step in this stage of the analysis was to use the ‘to do with’ categories in Table 7 as well as the sub-categories in Table 8 as a guide and to make another pass through the segments in the Master look-up table (which had already been coded according to the ‘to do with’ categories), but in this iteration, two questions were asked when considering each segment:

1) “Does this segment relate directly to any of the pre-defined modelling processes listed in Table 9 below, and if it does, to which one?” and
2) “What observable action phrase (using a progressive verb) could be used to describe the segment?”

Table 9: Pre-defined modelling process category codes

#	**Modelling processes**
0	Not relevant
1	Particularisation
2	Application
3	Realisation
4	Idealisation
5	Approximation

In answering the second question, that to do with the observable[5] action phrase that describes the student engagement, no limit was placed on the number of action descriptions that could be identified and no *a priori* names were specified, but it was noted that the use of *in vivo* names[6] (Creswell, 2013, p. 185) emerged naturally.

Initially a list of 18 action phrases emerged but with further iterations, in which further 'zig-zag' constant comparisons were made, the number of observable action phrases was reduced to 12; and these emergent action phrases are shown in Table 10.

Table 10: Observable action phrases derived from the 'to do with' categories

#	**Observable action phrases derived from 'to do with' categories**
1	Selecting a formula/example/concept
2	Applying a physics concept (reasoning)
3	Identifying a variable or a procedure
4	Verifying a formula/example/concept
5	Observing (examining, looking at the apparatus)
6	Taking action (doing, by way of a procedure)
7	Measuring (including dealing with uncertainty)
8	Confirming a measured or given value
9	Calculating
10	Presenting a solution, showing included/disregarded features
11	Verifying an answer (calculated or descriptive)
12	Exploring/familiarising (finding out about the apparatus)

The final step in this stage of the analysis was to characterise each of the segments in the Master look-up table in terms of the action phrases with which it could be associated. Each segment was related to a 1st and a 2nd choice action phrase as in many cases the segments related to more than one action phrase.

An example of the result of this 2nd stage of the analysis can be seen in Table 36: Appendix B: Extract from Master look-up table.

It is of note that from the point of view of the validity and reliability of the study (see Quality Assurance Plan below), the completion of this stage can be considered to be a

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[5] When using the term 'action' or 'action phrase', it is meant 'observable action' throughout.

[6] See section on validity and reliability for details regarding the naming of emerging categories.

quality assurance (QA) ‘hold-point’. By a QA hold-point it is meant a point in the overall process where the quality of the final result can be meaningfully influenced one way or the other and where a quality check of the work is important. The reason why this is an important point in the quality process is because this is the last time in the overall process where information and categories of student behaviour are observed directly; all subsequent information has to be inferred from what is captured and categorised at this point. An inter-coder test was successfully completed at this stage and details of the test are given in the section dealing with validity and reliability of the study.

3.7.4.1 Pictorial representation of the outcome of the 2nd stage

(Note: A summary of the pictorial presentation is given here, with the detail to be presented in Chapter 4.)
As a visual aid for the final step in the 2nd stage of the analysis, and in preparation for the 3rd stage, a spatial layout of the modelling processes proposed in the model-based view of physics (Buffler *et al*., 2008) was drawn on a sheet of paper. Then the observable action phrases that had emerged at the end of the 2nd stage of the analysis (Table 10) were superimposed on the drawing. This step was taken to facilitate the 3rd stage coding of the segments and in so doing, it became apparent that there was a discernible cyclic pattern within which student groups engage with minilabs.

From a closer examination of the sequence of the data segments it was evident that each of the observable actions was preceded, and followed by, a limited number of other actions. A process of axial and selective coding of these ‘entry’ and ‘exit’ paths was used to identify the paths, each of which was indicated by means of an arrow and when these were linked, the pattern shown in Figure 26 emerged. The findings and interpretation of this cyclic pattern are presented in the next chapter; suffice it here to point out that this pattern emerged from the observation of the data.

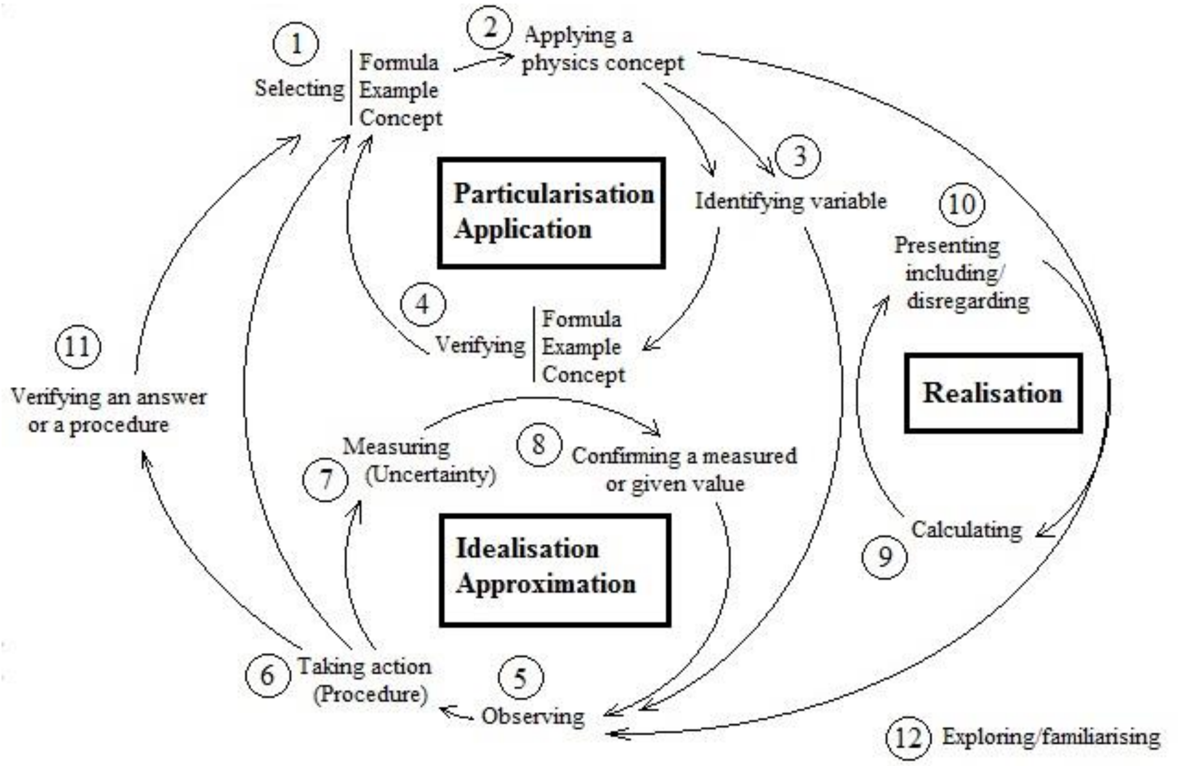

Figure 26: Emergent cyclic pattern in student group's engagement with minilabs

3.7.5 Third stage: Identifying strategies and reasons for using those strategies

The third stage of the analysis of the data is also characterised by an axial and selective coding process in that it was designed to allow for the emergence of the strategies, and reasons for adopting those strategies, through the interrogation of the segmented data through the lens of the modelling processes and the emergent observable action phrases. The use of grounded theory analysis in this stage may be considered questionable in that the imposition of the pre-defined modelling processes and the associated action phrases are 'forced', (see the section on validity and reliability for further discussion on this point). However, once this had been done, no limit was placed on the number or naming of the possible strategies that could be identified, nor was any limit placed on the number or naming of the reasons for employing those strategies. Furthermore, through an iterative process of constant comparison and grouping, the identified strategies and the reasons for their employment were allowed to emerge in a way typical of grounded theory analysis.

To facilitate the reading of this section, a reminder of what is meant by a strategy is presented here:

a) The devising of a strategy has been described as a metacognitive process, i.e., it is a process defined as having “conscious and deliberate thoughts that have other thoughts as their object” (Hacker, 1998, p. 8).
b) To employ a strategy means to formulate and execute an ‘overarching plan’ where the key distinction between a strategy and a plan is that a strategy is a cognitive engagement at a higher level than a plan (Scott, *et al.*, 1991).
c) In the context of this study: i) focussing on finding a formula would be a strategy, while actually looking for a formula would be an observable action; and ii) using the textbook to find a formula would be a strategy, while paging through a textbook would be an observable action.

As was the case in the second stage of the analysis, each of the segments in the Master look-up table was interrogated, but this time the questions asked of each segment were of a more specific nature and the coding was a two-part process. Given that by this stage each segment had been coded with respect to the 5 modelling processes listed in Table 9, as well as with respect to the action phrases listed in Table 10, each segment was interrogated as to whether a strategy could be inferred from the segment, and if so, what that strategy could be, and whether the reason as to why that strategy may have been employed could also be inferred.

As an additional step, where a strategy and a reason could be inferred, a question was included to indicate what may have prompted the use of that strategy and whether the strategy led to an outcome that was included in the presentation of the final solution to the problem or not. So, having identified a segment from which it appeared that a strategy could be inferred, the answers to the relevant questions matching the following associated statements were sought:

1) for *Strategy code*: “The student used the strategy of … ”,
2) for *Reason code*: “The reason this strategy was used was because … ”,

3) for *Choice code*: “The choice of this strategy was prompted by …” and
4) for *Usefulness code*: “Was this a useful choice in that it was something that contributed to the final solution to the problem. Answer is 0, 1 or 2 for unknown, yes or no respectively.

Once again, as was the case in the 2nd stage of this analysis, multiple passes were made through the segments during which the answers to the ‘strategies’ questions and the ‘reasons’ questions were developed and through constant comparison and categorising and re-categorising, the list of relevant strategies and their associated reasons emerged.

However, once this coding methodology had been applied to the full set of 1,314 segments in the complete Master look-up table, it became apparent that an extremely large number of *combinations* of ‘modelling/actions/strategies/reasons’ could emerge from the data so coded. Furthermore, many of these combinations would occur only occasionally in the students’ engagement. To deal with the large number of combinations, a final step in this stage was introduced which was designed to identify the frequency with which the strategies are used. The use of the strategies was categorised as: a) very often, b) often, c) regularly, d) seldom, and e) very seldom.

To make this step in the processing of the data and outcomes more manageable, but without loss of validity and reliability, a fully representative subset of the segments was chosen and since the coded segments were already in EXCEL© files it was straightforward to truncate the Master look-up table and then to analyse, through a sequence of data sorts, the distribution of the combinations of modelling/actions/strategies/reasons. The distribution of these combinations was determined by using a simple percentage calculation and from this the frequency of use was categorised. The complete set of sorting tables that were used to determine the dominant strategies and the associated reasons with regard to the modelling processes can be seen in Appendix A, Table 30 to Table 35.

It is necessary to note that the purpose of this final step was not to launch a detailed quantifying procedure, but merely to highlight the salient strategies adopted by the students with reference to the research questions. For this reason, no cut-off or threshold to determine whether a strategy was or was not considered to be relevant was established. The decision as to whether any specific combination should be considered relevant was done solely on the relative distribution of the combination in question and once the distribution had been determined, the employment of these strategies was categorised according to how often that strategy was used. The full list of emergent strategies that were employed by the students is presented in Table 11, the emergent reasons are presented in Table 12 and the emergent prompts are presented in Table 13.

Table 11: Strategies (complete list) showing frequency of use

Strategy	**Student employed the strategy of …**	Used
11	Following written or verbal instructions	Seldom
12	Following a pre-planned action	Very seldom
21	Focussing on selecting a formula	Often
22	Focussing on selecting an example	Seldom
23	Focussing on selecting a physics principle	Seldom
31	Itemising[7] (verbally) variables in a formula	Often
32	Itemising (verbally) step/s in a procedure	Very often
33	Itemising (verbally) physics concepts	Seldom
41	Announcing a value or a reading taken	Often
42	Announcing the prediction of the outcome of an action	Regularly
43	Announcing the result of a calculation	Seldom
44	Announcing an observation	Seldom
45	Announcing (asking) "what's going on", "what is this"	Regularly
51	Using as a resource the text book	Very seldom
52	Using as a resource self-generated notes (incl. rough)	Seldom
53	Using as a resource the internet	Very seldom
54	Using as a resource group members or other students	Very seldom
55	Using as a resource lecturer's class notes	Very seldom
56	Using as a resource the weekly problem sets (WPSs)	Very seldom
61	Checking on feasibility of a calculated value	Seldom
62	Checking on feasibility of a measured value	Regularly
63	Checking on feasibility of a procedure or an option	Often
71	Guessing uncertainty in a measurement	Seldom
72	Attempting uncertainty reduction by multiple readings	Seldom
73	Attempting uncertainty reduction by working from zero	Seldom

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[7] ***Itemising*** describes the strategy of making a proposal in a proactive, suggestive, point-for-point way, e.g., "we should do this, then that…, etc."
Announcing describes the strategy of saying something passively, in a matter-of-fact way, e.g., "the reading is…,"

81	Using data selectively by ignoring readings	Seldom
82	Adopting a 'null' solution to a problem/situation	Regularly
91	Letting a particular student take on the 'expert' role	Often
92	Simply trying something - exploring	Seldom
93	Presenting a multi-representational solution	Regularly
94	Announcing - that he/she is confused or "lost"	Seldom

Table 12: Reasons for employing strategies (full list) showing frequency of use

Reason	**Reason (Strategy was used because the student...)**	Used
0	No discernible reason	n/a
11	Had planned to do so beforehand	Seldom
12	Was responding to a written or verbal instruction	Very seldom
13	Was responding to a lead by other/s	Regularly
14	Was (asked) required to respond to this issue	Seldom
15	Wanted to enter into the engagement	Seldom
31	Wanted to foster a method or a procedure	Very often
32	Wanted to ensure procedural correctness	Very often
33	Wanted to correct what to them seemed incorrect	Regularly
34	Wanted to simplify the task (make easier)	Regularly
41	Wanted to verify (same)	Very often
42	Wanted to communicate a result	Regularly
61	Was not sure what to do or did not understand	Often
71	Wanted to reduce uncertainty in a measurement	Seldom

Table 13: Prompts that gave rise to strategies

Prompt	**Choice of this strategy was prompted by…**
0	No discernible prompt
11	An association with a formula
12	An association with an example
13	An association with a lecture
14	An association with a tutorial or WPS
21	A statement by group member
22	An action by group member
23	An observation made by a group member
31	Reading of/listening to a written instruction
41	The completion of a calculation or measurement

3.7.5.1 Linking the research questions to the identified strategies

Of particular importance to the outcome of this study is the information that emerges from Table 34: Appendix A: Distribution of strategies w.r.t. modelling & actions.

As noted earlier, the information linking the research questions to the identified strategies was done by doing multiple sorts on the segmented and coded data, see Table 36: Appendix B: Extract from Master look-up table. In these sorts, the focus was not on the absolute number of times the combinations were used, but on finding their relative frequency of employment.

The outcome of this linking process is presented in the next chapter.

3.8 Quality assurance plan adopted for the study

Throughout the present work, steps were taken to ensure the conceptual soundness of the validity and reliability of the study and from the outset it was recognised that in research guided by an 'interpretive epistemological orientation', such as the present work, the terms validity and reliability do not carry the same meaning as they would in quantitative studies where they are used as positivist quality criteria (Golafshani, 2003). And while there are many different conceptions as to what characterises the quality of qualitative research (Gall *et al.*, 2007, p. 473), for the purpose of this study, the definitions of these terms as proposed by Creswell (2009, p. 190) were adopted:

1) **Qualitative validity** means that the researcher checks for the accuracy of the findings by employing certain procedures, while
2) **qualitative reliability** indicates that the researcher's approach is consistent across different researchers and different projects.

It has been suggested by Golafshani (2003) that the test of validity and reliability - also sometimes referred to as 'trustworthiness' - is that qualitative research so managed will produce a "credible and defensible result" (Golafshani, 2003, p. 603). While it has been the goal to assure the quality of the research in the present work, it is perhaps necessary to repeat the point that it was not a requirement that the findings of the study should be generalisable, i.e., it was not the intention that it should be necessary for the findings to be generalised to any sites outside of the present context.

The approach taken in regard to the assurance of validity and reliability was to consider the validity structure described by Johnson (1997) in which it was suggested that there are three types of validity namely: 1) descriptive validity, 2) interpretive validity, and 3) theoretical validity. This structure is considered to be in accord with the definitions by Creswell above, in that descriptive validity refers to “the factual accuracy of the account as reported” (p. 284), interpretive validity refers to “the degree to which the research participants’ viewpoints, thoughts, feelings, intentions and experiences are understood” (p. 285), and theoretical validity refers to “the degree that the theoretical explanation developed from the research study fits the data and, therefore, is credible and defensible” (p. 296).

Apart from the procedures adopted to ensure validity and reliability, two other aspects of quality assurance were considered: those of ‘reflexivity’ (as the researcher was inside the study), and ‘language’ (as a significant proportion of the sample were not first-language English speakers).

3.8.1 Procedures adopted to ensure qualitative validity and reliability

3.8.1.1 Procedures to assure descriptive validity

The identified potential methodological threats to achieving descriptive validity were that the data captured would not be of a quality that would make it possible to answer the research questions, and that the transcribed data would be inaccurate or factually incorrect (Johnson, 1997; Creswell, 2007).

To ensure that the data would provide information at least adequate for the answering of the research questions a pilot study was done in the year (2010) preceding the one in which the actual data were captured (2011). A description of the pilot study, including all three methods of data collection, and the way in which the data capturing was modified as a result of the pilot is given at the end of this chapter.

To ensure that the data were accurately captured, the observations as well as the interviews were video recorded while the written submissions were those written by the students themselves. It is of note that while the student participation in regard to the observations and the interviews was entirely voluntary, the written submissions were compulsory in that students were allocated a nominal mark (5%) that went towards their laboratory year mark. Even though the mark was nominal, it was recognised that this incentive may have prompted the students to submit a written answer that they thought would be 'correct', rather than what they might actually have understood from their hands-on engagement; and other than to acknowledge that this may be the case, no procedure was put in place to control this threat to the descriptive validity of the study.

Table 14: Example of transcription showing context and interpretive information

Segment #	Student S#	Note on context (in italics) and **"Transcript" or written response**	**Researcher's memo**
89	39	*Refer to inc #69 & #70.* Guys, I am a bit concerned… (a discussion ensues about a misconception about the angles in question)	S39 has returned to the unresolved problem regarding the spatial arrangement of the field that he had earlier, see time 10:05. The other group members appear not have the same difficulty nor do they seem to see what is troubling S39; they appear largely to disengage from his discussion.

To ensure factual correctness when transcribing the videoed data, all of the transcription was done by the researcher and great care was taken to transcribe the student interaction verbatim. Throughout the transcription, notes were added in parenthesis in the "transcript" column to provide information on the context of the interaction (for instance, voice intonation, facial expressions, hand activity), and at the same time a researcher's memo was added to provide interpretive information. See Table 14 as an example. When including these comments, care was taken to keep these two categories of comment clearly defined.

Furthermore, in order to assure the validity and reliability of interview, of the total of 25 interviews conducted, 4 of them were conducted by one of the researcher's supervisors.

In capturing the written data, the procedure was much more selective in that the researcher made the decisions as to which aspects of the written work to capture and which to leave out. This selection was based on whether it was believed that whatever the student had written could contribute to answering some aspect of the research question. This has been recognised as a weakness in the descriptive validity of the study in that the researcher may have overlooked something that was indeed of importance.

To ensure the possibility of an audit trail, care was taken with the configuration of the segmenting process in that each segment was uniquely numbered and the source as well as the location of the respective item of data in the source was clearly noted.

3.8.1.2 Procedures to assure interpretive validity

The identified potential methodological threat to achieving interpretive validity was that, given the very narrow context within which the study was conducted, the researcher would impose an interpretation of the findings that was not supported by the data (Johnson, 1997; Barbour, 2001; Creswell, 2007). In regard to this threat there were three aspects to consider: 1) that the researcher, through contact with the students, would influence the student response during the hands-on engagement and thereby would ultimately influence the interpretation of the data, 2) that during the process of analysing the data, the researcher would ascribe incorrect or unsupported meaning and interpretations to segmented data, and 3) that the researcher would interpret the findings as a whole in an unsupported way.

The first point, 1) above, with regard to the researcher influencing the students and hence the actual data, as well as the researcher’s bias, will be discussed under the heading of ‘reflectivity’ below, while procedures to assure interpretive validity of the other two aspects 2) & 3) are discussed here.

i) Assuring interpretive validity through the use of grounded theory analysis

To ensure the interpretive validity in the coding of the segmented data, a grounded theory procedure was adopted. The actual application of the grounded theory procedure is presented in the relevant section on data analysis above, so in this section, attention is directed only at the quality assurance aspects of the implementation of the grounded theory.

From the outset of the study, cognisance was taken of the view by Glaser (1992) - in a critique of Strauss's later work in grounded theory with regard to the question of *Emergence vs. Forcing* - where Glaser states, "*Forcing* a property into a dimension family as an article of faith or a firm rule: 1) preconceives the data, 2) forces the analysis into a full conceptual description, and 3) derails from the theoretical analysis its grounded relevance" (Glaser, 1992, p. 46). It was therefore recognised that the imposed framework of the model-based view of physics would *perforce*, result finally in 'forcing' as defined by Glaser and consequently the analysis would not reflect a grounded theory analysis in every respect. Where, particularly in the early stages of the analysis, there was a requirement in the analysis to allow for the emergence of actions and student interactions, every measure was taken to adhere to the spirit of grounded theory analysis and to allow for a fresh perspective to emerge where the "hypotheses are the outcome of the study rather than the initiators of it" (Gall *et al*., 2007, p. 51).

To avoid a "drift in the definition of codes" (Creswell, 2009, p. 190), while the coding was taking place, the relevant interrogating question was clearly defined and carefully applied at each stage of the analysis, e.g., in the second stage of the analysis the interrogating question was: "*With what* (action or modelling) *is the student engaged here*?" The expectation being that the answer to this question would have the form, "(this segment has) *to do with* (progressive verb)." While in the third stage the relevant interrogation was focussed by sticking fastidiously to the requirement to complete the following sentence structures:

1) for *Strategy cod*e: "The student used the strategy of … ",
2) for *Reason code*: "The reason this strategy was used was because … ", and
3) for *Choice code*: "The choice of this strategy was prompted by …".

Further, in describing, classifying and interpreting data into categories via a coding process, three issues raised by Creswell (2013) were addressed namely: 1) *The use of* *pre-existing or a priori codes*, 2) *The origin of the code names* (something that ties in with theory-ladenness), and 3) *The counting and grouping of codes by number* (Creswell, 2013, p. 185). Since grounded theory requires that the theory should emerge from the process without the constraint of 'prefigured' codes the categories that were used in the analysis were allowed to emerge freely and were not limited by number or by description. Wherever possible, *in vivo* codes were avoided so as to avoid, as far as possible, an overly theory-laden interpretation and to try to allow for the emergence of conceptually surprising or unusual codes[8]. Finally, although the codes were numbered to facilitate sorting, the numbering did not imply a weighting or a quantitative tendency in the interpretation of the data.

ii) Assuring interpretive validity through the use of inter-coder agreement

To ensure the validity of the first two stages of the coding of the segments a check on a section of the coding of the segments was done by one of the researcher's supervisors. This inter-coder collaboration had two aspects. The data were looked at independently to identify strategies and these interpretations of the data. Later, different strategies were looked at independently (over a given set of data) to recognise segments where these strategies seem to be used. In both cases the interpretations were compared.

This check was done early in the stage 2 coding process and inter-coder agreement of >83% was achieved in both aspects, which, according to most authors on qualitative analysis, would be considered indicative for "good reliability" (Creswell, 2009, p. 191).

iii) Assuring interpretive validity through the use of triangulation

A key plank in the quality assurance plan of this study is the use of triangulation, a technique that has been described as an important methodological tool in qualitative research (Golafshani, 2003). More specifically and of relevance here, to ensure the

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[8] This approach is in contrast to the use of "low inference descriptors" recommended by Johnson (1997) where it is suggested that the use of the participant's actual language and dialect will convey information about the participant's interpretations and personal meanings.

interpretive validity of the coded data segments, the method of *data triangulation* was employed (Johnson, 1997, p. 289).

There is, in the literature, a range of interpretations of the role played by triangulation in the assurance of the quality of qualitative research (Golafshani, 2003). There are also various types of triangulation, e.g., using Denzin's topology, Cohen, Manion and Morrison (2011) have identified six types of triangulation: *Time-, Space-, Combined levels of-* , *Theoretical-, Investigator-* , and *Methodological triangulation*. However, as pointed out by Barbour (2001), "triangulation is difficult to perform properly", going on to explain that:

> Triangulation relies on the notion of a fixed point, or superior explanation, against which other interpretations can be measured. Qualitative research, however, is usually carried out from a relativist perspective, which acknowledges the existence of multiple views of equal validity. Therefore it does not readily lend itself to the production or observance of such a hierarchy of evidence (p. 1117).

With the difficulties described above in mind, the data triangulation in the present work had to be applied to data that were collected using three different methods (sources), viz., observed, written and interview material; from a number of different student groups; and from seven different hands-on tasks as the students engaged with those tasks. It was recognised that a potential methodological threat was that the method of triangulation could be applied selectively for as Barbour has suggested, "data collected from different methods comes in different forms and defy direct comparison" (Barbour, 2001, p. 1117).

The procedure adopted was to identify an event of possible interest within the segmented data and then to look for corroborating evidence in either or both of the other two data sources that may support the interpretation of the initial event. As a means to assist this procedure, when the initial transcription of the data was done, extensive use was made of cross-referencing, e.g., in Table 14, segment 89 is cross-referenced to segments 69 and 70. Since the data from the three sources were analysed together (after the academic year), and not sequentially as the data were collected, it is believed that the inclusion of the cross-references as and when these were noted was ‘acceptably efficient’, but there appears to be no way to verify this statement other than to test the validity in terms of the theoretical validity.

3.8.1.3 Procedure to assure theoretical validity

The identified potential methodological threats to achieving theoretical validity were quite simply that the theory that emerged from the study would not be “credible and defensible” (Creswell, 2009, p. 191). The achievement of theoretical validity relies in the first instance on the quality assurance of the descriptive and interpretive validity of the study, but ultimately it depends on the researcher’s ability to develop a theory that “moves beyond just facts and provides a (credible and defensible) explanation of the phenomenon” (Johnson, 1997, p. 285).

Of the strategies for assuring theoretical validity suggested by Johnson (1997) and Creswell (2009), four were adopted in the present work: 1) (the equivalence of) *extended fieldwork*, 2) *peer review*, 3) the use of a *‘thick’ description* to convey the findings, and 4) the search for *negative or discrepant information.*

The research was conducted over a period of four years during which time the researcher had time to develop a “detailed and intricate” understanding of the students and the setting in which they had to engage with the hands-on tasks (Johnson, 1997, p. 286). During this time the work was regularly reviewed by the researcher’s supervisors and discussions were held and presentations made of interim findings and interpretation of those findings. The findings were presented by way of a ‘thick’ description in order to provide the “many perspectives about the theme” (Creswell, 2009, p. 191). And finally, where they have been observed, examples that do not fit the interpretation and the developed theory have been highlighted and reported.

3.8.2 Reflexivity: recognising the role of the researcher in the study

According to Burrell and Morgan (1979), two contrasting perspectives, referred to as ‘subjectivist’ and ‘objectivist’, are evident in the practices of researchers investigating human behaviour and each of these two perspectives holds profound implications for educational research. These two approaches have led to the suggestion by Cohen, Manion and Morrison (2011) that a set of four assumptions underpin these two perspectives, referring to them as: a) assumptions of an ontological kind, b) assumptions of an epistemological kind, c) assumptions concerning human nature, and d) assumptions of a methodological kind. From each of these assumptions there emerges two images of human interaction, “one portrays (humans) as responding mechanically to their environment and the other as initiators of their own actions” (Cohen, Manion & Morrison, 2011, p. 6). A summary of these characterising assumptions, along with their subjective/objective dimension is depicted in Figure 27 and it was recognised that the view held by the researcher on each of the depicted characterising assumptions will have an influence of the choice of: research questions, kind of data sought, methodological concerns and the interpretation of the data.

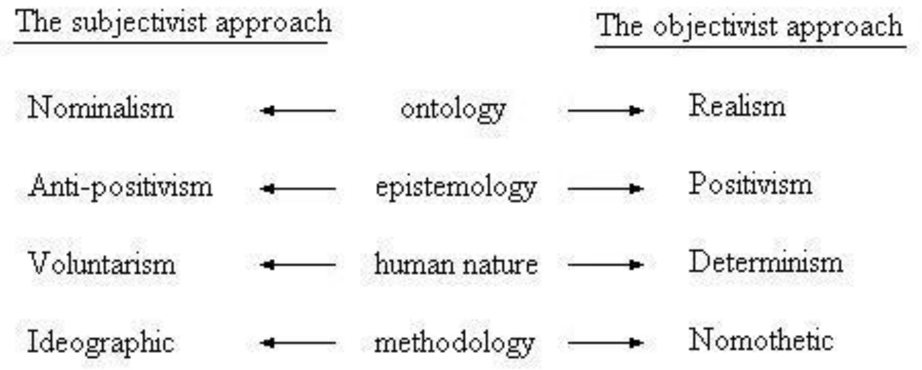


Figure 27: Assumptions with their subjective/objective dimension (Cohen *et al.*, 2011)

As far as the collection and analysis of the data were concerned, the researcher did not take a specific view on questions of ‘ontology’. However, in the development of the study there was, from the point of view of ‘epistemology’, a definite shift in the position of the researcher from a tendency to work from a positivist epistemology, to a non-positivist stance.

As far as the question of ‘human nature’ is concerned it was recognised throughout that the researcher was ‘inside’ the study, albeit under supervision, and so care was taken not to involve the researcher in other work done by the subjects, e.g., weekly problem sets, other laboratory work, etc., that would detract from the student-directedness of the strategies that students would adopt. This interpersonal distance was facilitated by the fact that the researcher only had direct contact with the students when they went to the laboratory to engage with the minilab tasks and while the researcher introduced certain aspects of how to engage with the minilab apparatus. And when he did so, care was taken to avoid leading the students' engagement in any meaningful way.

On the question of 'methodology' the adopted approach would be considered to be ideographic in that the study focussed on a specific context and no attempt was made to derive a generalised understanding of the answers to the research questions. The upshot of this is that although this aspect of the work was not considered in any rigorous way, the research could be described, overall, as having adopted a subjectivist approach.

It is significant that in the early stages of the present work, the question as to whether the student had got the answer 'right' or 'wrong' was considered. More specifically, the question asked by the researcher was whether the students' understanding of the physics concepts (as presented in the written submissions) were commensurate with the researcher's understanding of those same concepts. Fortunately this problem was identified soon enough and was corrected under supervision. Thereafter the submissions were considered with the focus on what was done and why, irrespective of the 'correctness' of the result.

3.8.3 Interpretation of language and the inference of meaning

Given that approximately 45% of the students in the sample are not first language English-speakers, particular care had to be taken to ensure that misinterpretations by both the subjects and the researcher are minimised. Multiple modes of communication (written and group and individual oral) were used to alleviate the potential for miscommunication and the interviews were structured so as to ensure follow-up questioning and probing for meaning whenever there was any doubt as to what was meant.

Table 15: Example of a student's understanding of a word being in doubt

Segment #	Student S#	Note on context (in italics) and **"Transcript" or written response**	**Researcher's memo**
848	8	*Ref Inc #847* Is…, you know when we added additional weight (touches the 40 g mass) isn't that (points to the bottom marker) equilibrium	S8 appears not to understand what is meant by the term 'equilibrium'
849	43	*S43 points to the lowest marker and the equilibrium marker while giving the explanation*. It (the mass) is not going below here, so it cannot be the equilibrium, you know, the undisturbed point. Can you see it is oscillating around this point (meaning a point of possible equilibrium)	S43 seems to have picked up that the problem has to do with the interpretation of the term 'equilibrium'

Whenever, during the analysis of the data, an interpretation had to be made of what the student may have meant, this fact was recorded in the relevant 'Researcher's memo'. In the example in Table 15, student S43 is a first language English speaker while student S43 is not. And while the term equilibrium has been used in lectures and weekly problem sets, there was doubt as to what the student actually meant, so these two segments were flagged accordingly.

3.8.4 Conducting a pilot study in 2010

Gall *et al.* suggested that a pilot study is one of the five major stages in a typical research process and that the purpose of the pilot study is to do small-scale testing of the procedures that are intended to be used in the main study (Gall *et al.*, 2007, p. 41). In the pilot study that was conducted for the present work, the feasibility of the minilab format, the integration with weekly problem sets, the duration of the minilabs (25 to 30 minutes), the observation techniques, the prescribed answer sheet, the interview method and a limited amount of collected data were tested and analysed.

The pilot study was done in the second semester of the year (2010) preceding the one in which the main study was undertaken and the cohort of physics major students who took part in the pilot study had enrolled for the same course as did the main sample in the following year.

Three of the seven minilabs, namely minilabs #5, #6 and #7, were used in the pilot study and the pilot sample size was 29 students out of a class of 73. All participation in the pilot study was voluntary.

8 observations were video recorded (3 of minilab #5, 3 of minilab #6 and 2 of minilab #7), 87 written responses in total were collected from those 29 students who were selected to be part of the pilot study sample, and two group interviews were conducted (one group of 2 and the other of 3). The students who were part of the pilot sample group were selected on the basis that they had engaged with all 3 of the pilot study minilabs.

Modifications and improvements that came about as a result of the pilot study were as follows:

1) *Observation*: A webcam was used in the pilot group observation and a much better camera was procured for the main study. The camera angle was changed from a top-view to a side-view so as to better capture students' interaction and to record the sound.

2) *Written*: Although the minilab tasks themselves were not changed in any significant way, the prescribed answer sheet that was supplied to the students was significantly altered. An example of the pilot study answer sheet can be seen in Figure 28, which can be compared to the answer sheet ultimately used in the study as shown in Figure 23 and Figure 24. The important differences in the answer sheets were that:

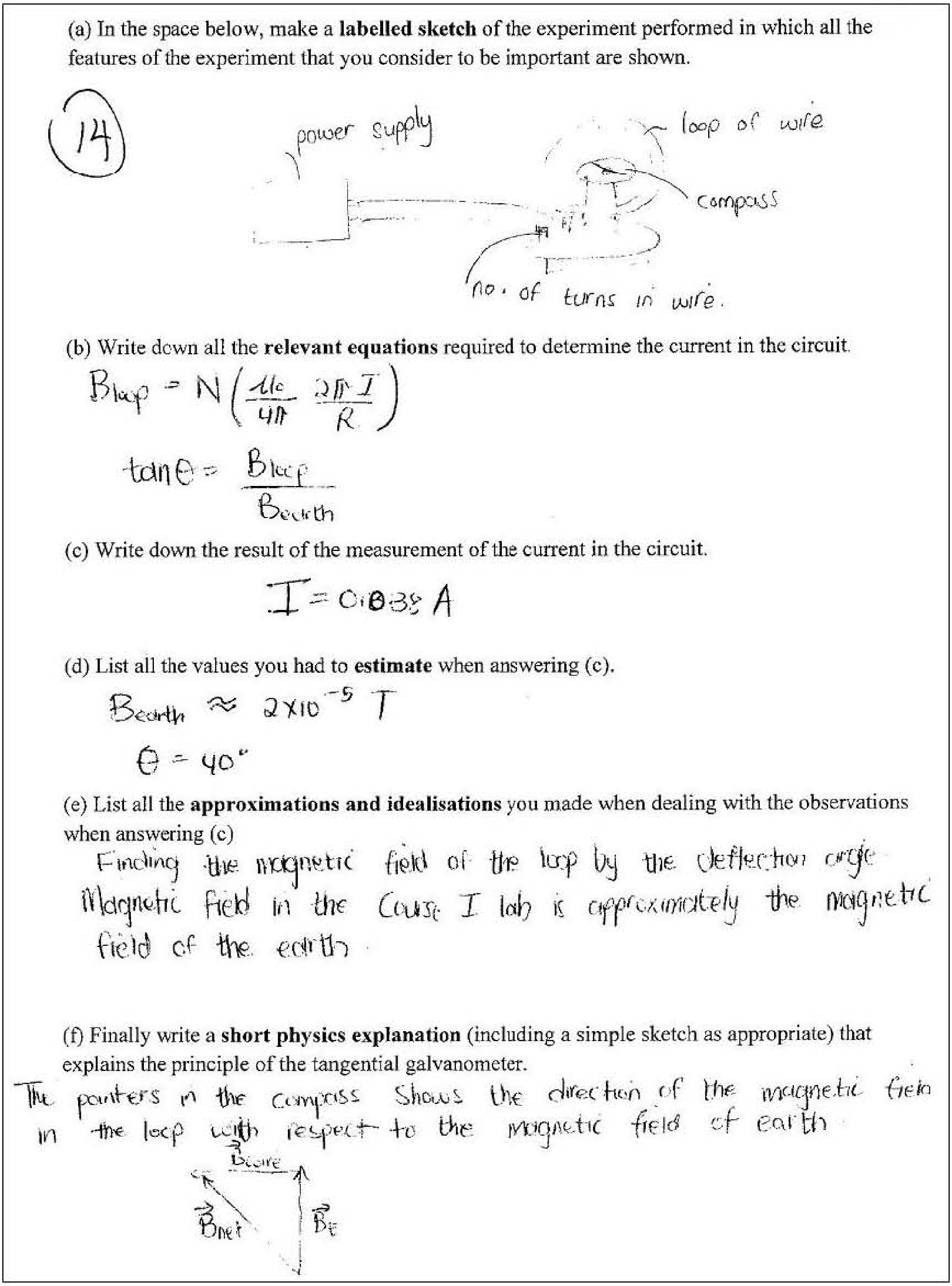
    a) more writing space was provided,
    b) more opportunities were created for students to give their answer to the minilab question in such a way that the answer could relate more directly to the research questions, e.g., the questions specifically asked students to list which physical feature of the experiment they included and which they disregarded,
    c) a prompt asking "why" they had made the choices they did was included,

d) the use of the words ‘approximation and idealisations’ were excluded as students thought they might have to make some formal response to these terms, and

e) instead of simply asking students to list what values they had estimated, they were asked to tabulate the variables within a pre-designed table.

3) *Interviews*: Two group interviews were conducted at the end of the pilot study. This method of interviewing was found to be unsatisfactory as it was not possible to delve into the observations of any one student. It was also not possible to discuss specific answers given by any one student. However, it was noted that group interviews did appear to allow for student dialogue which was useful in that the students appeared to be forthcoming in discussing the minilabs. It was also clear from the interviews done in the pilot study that the interview questions had to be more carefully structured, hence the format shown in Data source 3: Individual interviews.

4) *Reflexivity*: An important change that has to be reported is that it was recognised by the researcher’s supervisors that when viewing the recorded pilot interviews, the researcher had a tendency to attempt to help the students understand the phenomena, i.e., he would go into a teaching mode instead of letting the students’ “voice” be heard. This tendency was corrected in the main study by working within the more structured interview format.



14

(a) In the space below, make a **labelled sketch** of the experiment performed in which all the features of the experiment that you consider to be important are shown.

(b) Write down all the **relevant equations** required to determine the current in the circuit.

$$B_{loop} = N\left(\frac{\mu_0}{4\pi}\frac{2\pi I}{R}\right)$$

$$\tan\theta = \frac{B_{loop}}{B_{earth}}$$

(c) Write down the result of the measurement of the current in the circuit.

$I = 0.038$ A

(d) List all the values you had to **estimate** when answering (c).

$B_{earth} \approx 2\times10^{-5}$ T

$\theta = 40°$

(e) List all the **approximations and idealisations** you made when dealing with the observations when answering (c)

Finding the magnetic field of the loop by the deflection angle
Magnetic field in the Course I lab is approximately the magnetic field of the earth.

(f) Finally write a **short physics explanation** (including a simple sketch as appropriate) that explains the principle of the tangential galvanometer.

The pointers in the compass Shows the direction of the magnetic field in the loop with respect to the magnetic field of earth

Figure 28: Example of written response to the pilot study answer sheet

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4 Findings

In this chapter, tabulated strategies and reasons for using those strategies are presented initially. Then the adopted strategies are discussed in a ‘thin’ description with reference to each of the modelling processes. Finally the strategies are discussed in a ‘thick’ description with reference to the observed cyclic pattern that characterises the group’s engagement.

4.1 Strategies employed and the reasons for their employment

To facilitate the exposition of the findings, the strategies, and the reasons for their employment, are presented in Table 16 and Table 17. Note, the strategies that are very seldom used have been omitted from Table 11 to facilitate the reading of Table 16.

Table 16: Strategies employed by students when engaged in hands-on tasks

Student employed the strategy of:	Used
Following written or verbal instructions	Seldom
Focussing on selecting a formula	Very often
Focussing on selecting an example	Seldom
Focussing on selecting a physics principle	Seldom
Itemising (verbally) variables in a formula	Often
Itemising (verbally) step/s in a procedure	Very often
Itemising (verbally) physics concepts	Seldom
Announcing a value or a reading taken	Often
Announcing the prediction of the outcome of an action	Regularly
Announcing the result of a calculation	Seldom
Announcing an observation	Seldom
Announcing (asking) "what's going on", "what is this"	Regularly
Using as a resource, self-generated notes (incl. rough)	Seldom
Checking on feasibility of a calculated value	Seldom
Checking on feasibility of a measured value	Regularly
Checking on feasibility of a procedure or an option	Often
Guessing uncertainty in a measurement	Seldom
Attempting uncertainty reduction by multiple readings	Seldom
Attempting uncertainty reduction by working from zero	Seldom
Using data selectively by ignoring readings	Seldom
Adopting a 'null' solution to a problem/situation	Regularly

Letting a particular student take on the 'expert' role	Often
Simply trying something - exploring	Seldom
Presenting a multi-representational solution	Regularly
Announcing that he/she is confused or "lost"	Seldom

Table 17: Reasons for employing the strategies in hands-on tasks

Reason (Strategy was used because the student...)	Used
Had planned to do so beforehand	Seldom
Was responding to a written or verbal instruction	Very seldom
Was responding to a lead by other/s	Regularly
Was (asked) required to respond to this issue	Seldom
Wanted to enter into the engagement	Seldom
Wanted to foster a method or a procedure	Very often
Wanted to ensure procedural correctness	Very often
Wanted to correct what to them seemed incorrect	Regularly
Wanted to simplify the task (make easier)	Regularly
Wanted to verify (same)	Very often
Wanted to communicate a result	Regularly
Was not sure what to do or did not understand	Often
Wanted to reduce uncertainty in a measurement	Seldom

4.2 Strategies adopted with respect to each of the modelling processes

In this section the findings are discussed with respect to each of the five relevant modelling processes and while the focus is on each of the strategies used, they should not be viewed in isolation. The modelling processes need to be considered in terms of the combination of the *observable actions*, the *strategies* employed, and the *reasons* for that employment.

As noted in the previous chapter, there are a great many possible combinations of *modelling processes/actions/strategies/reasons* that may be identified and so a method, based mainly on the density of their distribution within the coded segments, was devised to select the most commonly used combinations. However, it was noted that this was not the only way in which a strategy could be identified as having had a significant influence on the outcome of the students’ engagement. When a combination of an action, a strategy and the reason for employing the strategy was considered to be insightful in the process of modelling, even though it may have been employed infrequently, then that combination was included in the presentation of the findings. Where such a case has been included it has been highlighted in the text.

4.2.1 Particularisation strategies

The reader is reminded that *particularisation* is the process to name specifically, to itemise or to state in detail some aspect of scientific theory. Particularisation states the relevant abstract formalism (i.e., the mathematical expressions, logical constants and non-logical terms) as well as the relevant rules of correspondence (i.e., the co-ordinating and operational definitions, semantic rules and epistemic correlations) associated with the particularised aspect of the theory. Particularisation provides the partial interpretation of some aspect of the theory that is to form the framework of a physical model.

Having considered the combinations of modelling processes/actions/strategies/reasons shown in Table 30 to Table 35, the dominant strategies and associated reasons with regard to particularisation are presented in Table 18.

Table 18: *Particularisation*: Salient strategies and reasons for their employment

Student employed the strategy of:
Focussing on selecting a formula (in preference to a physics principle).
Itemising (verbally) variables in a formula as they appeared in a formula.
Reason (Strategy was used because the student...)
Wanted to ensure procedural correctness.

The complete list of observable action phrases are tabulated in Table 10, and of these, the dominant observable actions related to particularisation were:

i) the steps taken to select a formula or an example and

ii) the way in which the variables to be evaluated in the solution to the problem were identified.

From Table 31 (codes 21 & 22 vs. code 23), it can be seen that in seeking to resolve the requirement to particularise an aspect of theory, students were about three times more likely to particularise by focussing on a formula or an example, rather than to engage with the problem by considering, by way of discussion, a physics principle.

4.2.1.1 Example (1) of strategies in particularisation

As reported, student particularisation is dominated by the strategy of finding a formula that ‘works’, and from that formula, the following strategy is to identify the variables that need to be quantified.

In minilab #3, conservation of energy, in which a mass oscillates on a spring, the particularisation of the theory required that students had to consider whether or not to use a physical model that required them to determine the kinetic energy of the oscillating mass. This question arises since the family of physical models to do with the conservation of energy of this type often uses the statement $P.E. = K.E.$ as a central theme, and in which the equation $K.E. = ½\, mv^2$ is incorporated. The ubiquity of the statement in problems of this sort is illustrated by the following observed comments:

- In minilab #3, case #1, at location #02:03, student S68 states, “Ok, so we are going to have to find the velocity in the middle (of the oscillation).”

- In minilab #3, case #2, at location #20:01, student S43 says, “We need the kinetic energy of the mass, so we need (to know) the masses.”

- In minilab #3, case #3, at location #00:56, after a brief discussion about the formula they have to apply, student S65 says, “This is just the same as we did yesterday (a problem in class in which kinetic energy was determined) except now we are taking away the 40 grams instead of adding it.”

- In minilab #3, case #5, at location #00:34, student S41 asks, “How do we get the kinetic energy?” to which group member student S5 replies, “Kinetic energy is equal to potential energy, but it is just at a different place.”

However, in this problem, the solution lay in determining the energy stored in the spring using a model that incorporates the equation $U = ½\, kx^2$. To illustrate the way in which students use the strategy of choosing equations and then identifying relevant variables, an example of how first one physical model is particularised, where the kinetic energy is to be determined, and when it becomes apparent that that model cannot be applied because no means have been provided for the students to measure the instantaneous velocity of the oscillating mass, another physical model is chosen.

Because the interaction in this example is quite dense, it is shown in tabular form in Table 19. The interaction is presented in its entirety as it illustrates the possibility that "there are particular pedagogical advantages in the view that the process of physics problem-solving occurs at the level of the physical model" (Buffler et al., 2008, p. 432) as these students attempt to make sense of the physical model.

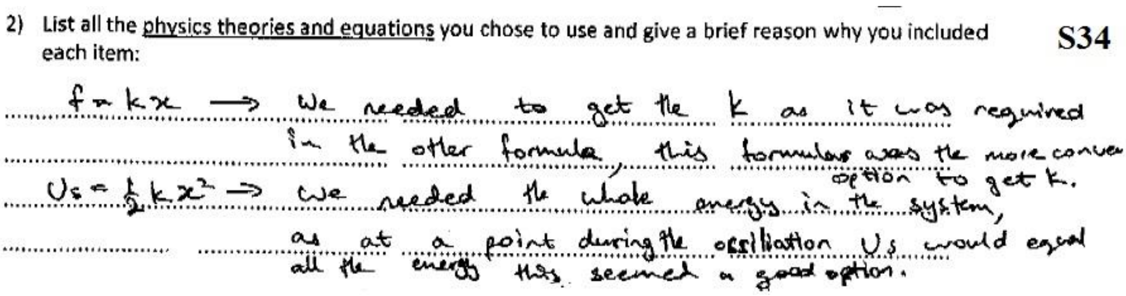
Table 19: Example to illustrate student engagement in particularisation

Segment #	location #	Student S#	***Note on context (in italics)* and "Transcript" or written response**	**Researcher's memo**
856	18:50	8	*After a discussion about the energy in the system, S8 responds to a suggestion by student S43, who has taken the lead in the discussion*, So we need to (calculate) total energy?	Previously, one of the students in the group, S43, has proposed a physical model in which kinetic and potential energies are equated.
857	18:55	43	Total energy is equal to that (points to something on a page), '*U*' is equal to '*mgh*'.	S43 is looking at equations written on a piece of paper and appears to be listing possible equations.
858	19:05	43	… what other equations…, 1/2 mv^2.	S43 appears to continue to list equations .
859	19:20	43	Because total energy is '*U*' plus '*KE*'…, but '*U*' is also equal to…, '*U*' is equal to that (points to the page)	S43 appears to be going through combinations of equations.
860	19:43	8	*S8 once again suggests a step in the procedure*, So (inaudible) (we) must work out '*k*'.	S8 appears to be wanting to engage with S43 by drawing her attention to the spring constant while at the same time looking at S34, the third student in the group, to find out what he is doing.
861	20:00	43	We need the potential energy…, and the kinetic energy of the mass.	S43 appears to ignore the prompting by S8 and repeats, more or less, what had been said earlier (ref 854).
862	20:05	43	So you need the masses…, it will be just on this one (points to the 100 g mass).	S43 appears to be prompted by the formula to itemise the mass.
863	20:40	8	*S8 tries once again to engage with S43 on the steps to be taken*, But he said, that work was being done when you remove this mass (holding the 40 g mass)…, and work was being done when you add this mass, that's true yeah?	S8 makes reference to something that 'he' had said, it is not clear as to who 'he' is.
864	20:50	43	*S43 continues to itemise variables in the formulas,* '*h*' is going to be our amplitude.	S43 is referring to the '*h*' in the formula for potential energy '*mgh*' written on the paper in front of her.
865	21:00	8	*S8 repeats something she said earlier*, (ref 853) Isn't kinetic energy plus potential energy equal to 1/2 kx^2.	S8 once again appears to suggest a different physical model to the one S43 appears to have in mind (ref 853)

866	21:05	43	*S43 recognises that a different physical model has been suggested and responds with why it cannot be used*, Ja, but you need total energy to work out ‘*k*’.	S43 has taken note of S8’s suggestions for the first time.
867	21:15	8	But do you need to work out ‘*k*’.	S8 appears to be unsure.
867	21:16	43	No…, because we need the energy at the beginning and the energy at the end.	S43 appears still to be intent on using the physical model that incorporates *KE*.
869	21:30	8	The energy at the beginning would be the kinetic energy plus the potential energy	S8 seems to repeat what S43 has in mind and appears ambivalent.
870	21:50	34	What about the (inaudible) spring	S34 has taken part in the present discussion for the first time and he concentrates on the spring properties.
871	21:55	8	The spring energy…, isn’t that the total energy…, Ja.	S8 takes a cue from S34 and repeats what was suggested earlier (ref 865).
872	22:00	8	We actually do need to work out ’*k’* so that we can get the total spring energy (ref 867) because this will give us how much energy is going up and down (indicates the oscillation by hand).	S8 has made a definite proposal to use a different physical model to that proposed by S34.
873	22:12	34	Remember he said the energy moves from one part to another.	S34 refers to something 'he' had said and appears to reinforce what S8 has said
874	22:25	8	But remember he said not all the energy moves…, so we need to work out our total energy.	S8 agreeing with what S34 has said about what 'he' had said, and also adding to the comment.
875	22:30	43	So we need to find ’*k*’ to work out total energy.	S43 agrees with the proposal that ‘*k*’ has to be determined (ref 867).
876	22:31	8	Yes.	
877	22:32	43	But how are you going to work out ‘*k*’ without anything…, (recites) Force equals *kx*…, right…	S43 asks the question and then answers it herself by reciting Hooke's Law $F = kx$.

In this example, student S43, who is the dominant character in the group, appears to adopt a strategy of choosing, from a piece of paper in front of her, formulas that are relevant to this class of problem. And having chosen a formula from the list, S43 appears to adopt the strategy of checking to see whether this formula will be suited to solving the problem by itemising the variables in the formula. One of the other members of the group, S8, appears to know that it is necessary to determine the spring constant k but is unsure, and so seems to guide S43 tentatively in that direction. In the final segments of the presented sequence, S43 realises that a different physical model is required (segment #875), and then works out how to determine k by reciting Hooke’s Law (segment #877).

The written submission by student S34 in response to question 2 in the questionnaire illustrates the way in which the observed formula-driven approach is carried through in the written work:



2) List all the physics theories and equations you chose to use and give a brief reason why you included each item: **S34**

$f = kx$ → We needed to get the k as it was required in the other formula, this formulas was the more conve option to get k.

$U_s = \frac{1}{2}kx^2$ → We needed the whole energy in the system, as at a point during the oscilliation U_s would equal all the energy this seemed a good option.

4.2.1.2 Example (2) of strategies of particularisation

The second example of the strategy of focussing on a formula to particularise an aspect of theory comes from the articulation of this method by student S70 during an interview. Student S70 had been observed along with students S5 and S41 in minilab #3, case #6.

In the interview, S70 and the interviewer watched an extract from the recorded observation in which the group was searching to particularise some theory to use as the framework for the required physical model. In the observation, the three students had already recorded the amplitudes of the oscillating mass, i.e., they had collected the necessary data, but they had no particularised theory to formulate an appropriate physical model that would provide the solution to the problem. They had been discussing the potential energy of the oscillating mass with respect to the energy in the stretched spring and the energy due to the position of the mass in earth's gravitational field and at location #11:19 (of the S70 A interview) student S5 says quite suddenly, "Oh, oh, remember that *F* = *ks*, right?" to which S70 responds, "Oh, so we can work out *ks*, ja…, that's the point!"

The relevant transcript of the interview (S70 A) follows:

34:37 I: That looks like a nice break-through point. You had your data, and now you start to work out what you have to do with the data.

34:39 S70: Ja…, I am actually just remembering what the problem was…

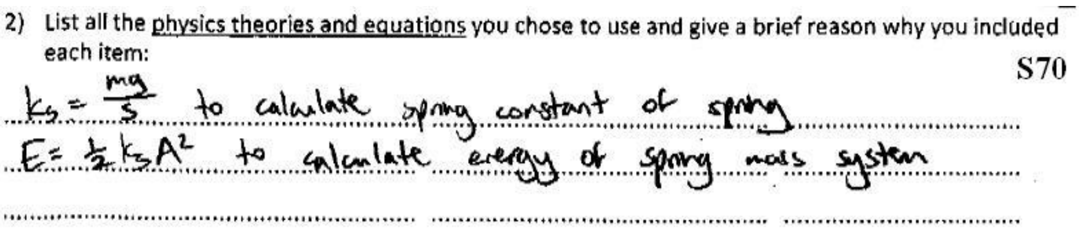
34:44 S70: Often with these things it is easy…, you can kind of work out what you need to be measuring just by looking at the formulas and seeing… ok we have got this equivalent and you can work out… but ja…, sometimes you do it a bit backwards.

35:00 I: Does that have to do with planning the experiment?

The student and the interviewer have a brief discussion about planning the engagement.

36:37 S70: (In planning) you can look at this [points to the equations on the written submission] and say…, ok, in this formula we have got '*e*' and we need '*a*', "*ks*", we've got a spring… you know, and then take some readings.

The written submission by S70 is typical and very similar to that by S34 in example (1) above:



2) List all the physics theories and equations you chose to use and give a brief reason why you included each item:

S70

$k_s = \frac{mg}{s}$ to calculate spring constant of spring

$E = \frac{1}{2} k_s A^2$ to calculate energy of spring mass system

The strategy of selecting a formula, and from that selection, itemising the variables to be measured, is typical of the way in which several students particularise. However, the precise reason why the students use these strategies, other than that they are successful, is not revealed in this study. In the overall findings it is evident that students are very motivated to "get it right", which comes through in the way in which they constantly verify and check every step and procedure, and it is possible that these strategies are selected simply because they work.

4.2.2 Application strategies

The reader is reminded that *application* is the process by which a particularised scientific theory is applied in the formulation of a physical model. The application includes incorporating in a physical model some or all of the particularised mathematical expressions, logical constants and non-logical terms, as well as the relevant co-ordinating and operational definitions, semantic rules and epistemic correlations.

Having considered the combinations of modelling processes/actions/strategies/reasons shown in Table 30 to Table 35, the dominant strategies and associated reasons with regard to application are presented in Table 20.

Table 20: *Application*: Salient strategies and reasons for their employment

Student employed the strategy of:
Itemising (verbally) the variables in a formula.
Itemising (verbally) step/s to be taken in a procedure.
Announcing the prediction of the outcome of actions or steps to be taken.
Announcing (asking) questions such as "what's going on", "what is this"?
Announcing that he/she is confused or "lost".
Reason (Strategy was used because the student...)
Wanted to foster a method or a procedure.
Wanted to ensure procedural correctness.
Wanted to correct what to them seemed incorrect.

The complete list of observable action phrases are tabulated in Table 10, and of these, the dominant observable actions related to application were:

i) identifying the variables in a formula,
ii) verifying a formula (that has been particularised),
iii) applying a physics concept (i.e., reasoning)
iv) identifying steps in a procedure, and
v) taking action, i.e., ‘doing’ by carrying out a procedure.

Incidentally, from Table 31, which shows the frequency and % use of the strategies, it can be seen that in selecting a reference for information, (codes 51 to 56), students are most likely to consult their self-generated notes as a resource, and were least likely to consult the *Matter & Interactions* textbook.

As before, the reasons for adopting these strategies were generally to foster a method or a procedure and once again the students took due care to ensure procedural correctness. In the main, when there was observed confusion or disagreement, group members readily responded by making it clear that they “did not understand” or were not sure as to why the group was doing what it did.

4.2.2.1 Example (1) of strategies in application

In this example, which is taken from minilab #6, case #1, crossed magnetic fields, and presented in Table 21, student S42 shows how the application of a particularised formula is driven by the strategy of itemising the variables in the particularised formula. In this example, S42 itemises variables in segments 13, 16, 29 and 31, as if to summarise, i.e., “We have this, we have that, etc.” The strategy is to draw attention to the variables and thereafter to turn the attention to the apparatus where the real world equivalent of the itemised variable may be identified.

Table 21: Example to illustrate students itemising variables in application

Segment #	location #	Student S#	***Note on context (in italics)* and "Transcript" or written response**	**Researcher's memo**
11	02:16	42	*S42 is looking at a formula and picking on a specific item in response to S24*. Do we know the size of the loop? (*By implication, the area of the loop.)*	Prompting the measurement of a variable.
12	02:20	7	*S7 also picking on that specific item in response to S24*. Do we know how many times it is coiled? (Indicates circles by hand)	Promoting the measurement of a variable.
13	02:30	42	*Summarises*: So we have a loop (draws a loop), we have how much... 6 volts (looking at the power supply)… the magnetic field is… (pause).	S42 appears to be going through a checklist.
14	02:55	42	*Turning to S24*. Can you remember the formula?	It has been 3 minutes from the start of the exercise.
15	03:00	24	*S24 Having paged through his notes for some while*. So here we go, coils, *N* turns, (pointing to the equation) so we will need the area.	Formula centred-strategy in operation.
16	03:10	42	*To this point S42 and S24 have ignored S7 and S39,the other two members of their group*. *Each pair continues to make notes and identify variables and formulas*. $\mu = NIA$, we have *B*… (Still without engaging with apparatus.)	The group had been formed with two pairs of partners, meaning that the partners in each pair had worked together before, but the individuals in the pairs had not worked together.
17	03:10	24	*S42 has pointed to the fact that there are two formulae written on the paper*. You can ignore this formula.	Selecting a formula.
18	03:45	7	*S7 Having read the task worksheet in which the orientation was specified*. This thing has to be orientated so that... (turns the apparatus to its correct position) it is perpendicular to the… (shows by hand).	Student S7 is applying a written instruction.
19	03:45	24	*S24 responds to the action by S7 while S42 ignores what is being said.* It doesn't have to (be orientated in a particular way). We just have to measure the angle.	Neither S24 or S42 appear to have read the instruction on the worksheet regarding the requirement to orientate the apparatus in a specific way.
20	03:45	7	*S7 Pointing emphatically to the notes with both first fingers*. It says over here… (he reads the instructions from the task sheet). (location#	S7 appears to understand why the instrument has to be orientated in a particular way.

			04:05) It has to be like this… (Shows by hand).	
21	04:15	42	*S42 Pays attention to the apparatus and realises that the scale can be turned*. So then you will get a direct deflection. What you need to do is to get that between 70 and 70…? You want 90°.	S42 seems no longer to contest the question of the orientation of the apparatus (ref 19).
22	04:25	7	What I have done is make it look as perpendicular to this side (indicates with hand) as possible.	S7 showing that he has worked out the correct orientation (roughly).
23	04:30	7	*S7 Has noted that the scale can turn*. So, can we actually turn this? (Referring to the compass).	
24	04:35	42	*S42 turning the scale, sets it so that the rest condition has the needle at 'zero'*. (Orientating it like that) makes it so much easier.	The implication here is that the student means easier in that an initial reading does not have to be subtracted from a final reading.
25	04:40	7	You might as well leave it on zero and we can get the deflection straight out of that.	S7 appears to agree with S42 about the setting of the scale to start at zero.
26	04:50	42	*Having orientated the apparatus correctly, all four members in the group make the sketch and appear to agree that they have the correct start to the problem.* That's perfect. We put the coil across like that, we put the compass across like that, we put zero here.	Setting the scale to 'zero' has relevance for the strategies adopted when approximating the value of a variable.
27	05:00	24	*S24 makes an unsolicited comment*. This is actually very similar to the problem set (WPS)	Student is verifying what they are doing by comparing with a WPS
28	05:05	39	One of the problems in the weekly problem set, yes.	S39, who to this point has not taken part in any of the discussion, is in immediate agreement
29	05:10	42	*Summarises from the equation again*. So we can get '*NIA*', we don't know what '*I*' is,	Ref Inc# 7, 18 & 20. S42 appears to go through a checklist again.
30	05:15	39	We are supposed to determine '*I*', that is the question.	Ref #28, S39 states the aim of the minilab which is written on the question sheet.
31	05:30	42	*Appears to go through a checklist again by summarising - again from an equation*. So we need *A*, we need *N*, we need *R*, we need 4π, and B_{earth}, which is 25 micro tesla horizontal. (Repeats) We just need area, the number of coils, and *R*. Did he give us the number of coils?	Ref Inc. 7, 18 & 20. Student employs a 'check-list' strategy to identify variables.

In an interview with S42, while watching the sequence in Table 21, the interviewer stopped the recording just after S42 and S7 had asked, in segments #11 and #12, "Do we know the size of the loop?" and "Do we know how many times it is coiled?' and the following discussion took place:

06:15 I: There were two questions there (segments # 11 and #12). What was the size of the loop and how many turns in the loop? Do you remember what may have prompted those questions?

06:26 S42: I think it was just because we were doing it in class and aah… I can't remember exactly, I can't remember all the formulas and stuff, but I seem to remember, you had the loop number [shows a loop by hand] and there was something to do with the radius as well…, but it was something we had done in class.

06:45 I: You had done that problem two or three days before hadn't you?

06:50 S42: Ja…, possibly even that morning, I can't remember.

That the students had done a similar problem before was confirmed while watching the recorded sequence when students S24 and S39, in segments #27 and #28, said that the problem was similar to what had been done in a weekly problem set (WPS). This may have been the reason why the engagement with the minilab appeared to be so focussed on the formulas and the strategy of itemising variables from a formula. Even so, this strategy was observed throughout the study as being typical of the way in which the application is conducted.

4.2.2.2 Example (2) of strategies in application

Generally, observing the application of a theory is not clearly distinguishable from the process of particularisation of that theory. However, when some defining condition of the proposed particularisation has to be met in order to apply the theory, the application strategies *per se* may be more readily observed. In minilab #6, crossed magnetic fields, there was just such a defining condition that had been highlighted in the information sheet given to the students along with the question. The defining condition was, "The wire loop has to be orientated so that the normal of the area enclosed by the loop is perpendicular to the earth's local magnetic field."

Unbeknownst to the students, before any group was given access to the tangential galvanometer they were to use in the engagement, that apparatus had been turned by the researcher so that its orientation was not in the position it needed to be in order to get a suitable reading. The purpose of turning the apparatus was to see how the students would work out a procedure for the successful application of the summing of crossed magnetic fields which required that the fields be orthogonal since the calculation ultimately involved the given equation,

$$\tan\varphi = \frac{B_{coil}}{B_{earth}}.$$

In minilab #6, case #4, the discussion to be observed at location #02:00 shows that the students believed they had a reasonable sense of what was to be done in the minilab which leads student S70 to say:

> At location #02:10, “It looks like it is kind’a simple.” A short while later, at location #05:15, they realise that the alignment of the compass magnet is not either in line with, or perpendicular to the loop, but they conclude as articulated by S63, “It does not matter because we just want to measure deflection.”

The students proceed to take readings of the deflection of the magnet by turning the power supply on and off. A discussion about the spatial orientation of the earth’s magnetic field follows and after a careful inspection of the apparatus they work out exactly how to identify the magnet in the compass and by now they have realised that something is amiss. At location #12:19 the following interaction, shown in tabular form in Table 22, ensues. As the interaction is quite dense, it is felt necessary to present it in its entirety for completeness.

Table 22: Example to illustrate student reasoning in application

Segment #	location #	Student S#	***Note on context (in italics)* and "Transcript" or written response**	**Researcher's memo**
1007	12:19	68	*After a bit more discussion about the direction of the deflection, S68, who has been looking intently at the apparatus for some time,* Hang on, hang on, hang on…, let me just, *turns the whole galvanometer.*	This adjustment orientates the loop properly in $\boldsymbol{B}_{\text{earth.}}$
1008	12:43	68	*S68 proceeds to adjust the compass so that the needle is on zero …* ok…,	The power was turned off.
1009	12:48	68	*S68 turns the power on - having orientated the loop and the compass correctly - and sees a different deflection to what the group had read when the loop was incorrectly orientated.* No…, come off it…, why is it (the deflection) so much different (*ref* 1010).	This deflection is different because the whole apparatus has been turned. Note that (at *ref* 984) the students had concluded that this did not matter as it would not change the deflection.

1010	12:56	68	Ok (laughs) it is because…, remember if it is parallel to the magnet then the magnitude of the deflection is going to be nought. (*ref* 1009).	S68 appears to draw on the solution to a problem that was done in class. In that case the requirement was to find the orientation of the loop's magnetic interaction would be a maximum.
1011	13:14	70	And the deflection is going to be a maximum when it (the loop orientation) is 90°.	S70 appears to draw on the same solution.
1012	13:15	68	And it (the galvanometer) was at an angle so now the deflection is going to be more (*ref* 1009 & 1017).	S68 reconciling the difference in readings before and after the orientation of the galvanometer.
1013	13:17	70	Oh but wait, wait…, wait, that is the magnet dude… so now surely this should be…	S70 appears still to be working out what the spatial arrangement of the two fields may be.
1014	13:26	68	No, because the magnetic field is working along this axis (shows by hand) … so now it is proper (meaning correct?)	S68 seems to have developed a confident explanation for the orientation of the galvanometer.
1015	13:36	70	*S70 steps back*, So which one (of the readings) do we use? *Note: The implication in the question is "which reading is correct?"*	S70 seems to step back to avoid confrontation and appears unconvinced of S68's call that the second reading is 'proper' (correct?).
1016	13:38	68	I would say the second one (*ref* 1015).	S68 seems confident of his explanation but is not adamant.
1017	13:59	41	*S41 has not engaged with the conversation to this point*. But the deflections are different and now we have a different (angle) theta…, and the same current, and the same magnitude of $\boldsymbol{B}_{\text{earth}}$.., so…, it doesn't make sense.	S41 and S70 seem to have missed the point made by S68 earlier as to why the deflections are different (*ref* 1012) Students still seem to think the orientation of the apparatus is immaterial.
1018	14:18	63	*S63, who has not said anything until now, engages with this discussion*. Well, it would seem less arbitrary to use this one (reading with the loop orthogonal) rather than some random angle (which it was when they started the minilab).	By this response, S63 appears not to have actually worked out why the loop has to be perpendicular. Moreover, S63 appears to favour the second reading because it is not off 'some random angle'.
1019	14:24	41	*S41 supports the orthogonal option by reverting to an instruction she had heard.* So now it is perpendicular, and that is what he said. He said you should try and get it perpendicular.	'He' is possibly the researcher, who had spoken to the students about the orientation of the earth's magnetic field before their minilab engagement.
1020	14:30	70	*S70 has in the meantime made minor setting adjustments to the apparatus, turned it on, and taken the deflection reading*. Ja..., that is exactly 50 degrees… that should work quite nicely.	S70 has carefully set the compass so that the needle is at 'zero' on the scale when the power is off and clearly likes the idea that the reading is a whole number when the power is on.
1021	14:40	41	So we use that (deflection of 50 degrees) because we lined up the magnet (in the compass) at a 90 degree angle (to the plane of the loop).	S41 appears to be checking why the second reading should be used.
1022	14:45	70	I am still not convinced that… it seems that (the second reading) was the best one to use…, but why…	S70 still has not reconciled the reason for the choice in result (*ref* 1027).

1023	15:20	70	*All four students start reading the work sheet which they have had all along but have not read until now. Then S70 notes the instruction*. Oooh, ok there we go…, basically we need to know what direction the earth's magnetic field is..., because the normal of this area (the loop) needs to be perpendicular to whatever that (the earth's) magnetic field is…	The instruction reads, "The wire loop has to be orientated so that the normal of the area enclosed by the loop is perpendicular to the earth's local magnetic field."
1024	15:44	68	It helps to read… (smiles)	S68 has made this remark with a wry smile.
1025	15:53	68	*S68 then points to the equation, which is a 'tan' function, given on the work sheet*. So that formula is on the basis that it is perpendicular.	
1026	15:59	68	Of course, you cannot use 'tan' if it is not a right-angle triangle.	S68 gives an explanation for the orientation of the loop (*ref* 1022).
1027	16:13	68	Now it makes sense… *All four students laugh and nod in agreement*.	

In this case the students had applied the physical model as they had done in the equivalent classroom exercise and they appeared to know what to measure and how to obtain the necessary readings. They had also recognised that somehow they had not matched the application of the theory to the real world condition. In segments 1007 - 1016 students S68 and S70 applied the strategies of itemising the procedures and predicting outcomes with reference to the theory and the real world situation in order to resolve this question. In the ensuing interplay between theory and observation they not only made sense of the particularised physical model, but the group also made the ‘discovery’ of an important concept that underpins the application of the mathematical expression that was embedded in the physical model (segment 1026).

At segment 1017 student S41 engages with the group by using the strategy of stating that he/she was not sure what to do or did not understand, i.e., “… it doesn’t make sense”. In the subsequent interview, after watching this clip, the interviewer stopped the recording (segment # 1231 onwards) and asked S41 what it was that happened for it to “make sense”:

08:30	I:	What made you change your mind? What made it clear to you?
08:40	S41:	Ah… [after thinking about it for a moment] well, S68 reminded me about the 90° [positions hands perpendicularly]…, obviously because it is a right angle cross-product thing. And the sine of 90° is one. So that (position) is going to make the biggest difference. That would give us the biggest deflection.

It is of note that in the similar problem that had been presented in class a day or two before, the requirement was to determin the orientation of the loop so as to ‘give the greatest deflection’ in the compass needle; and it is suggested that what made the solution to the minilab coherent for S41 was that these two problems were complementary.

When problem-solving of the kind illustrated in the above example was observed, a note was made of the resources (such as notes, written instructions, weekly problem set examples, etc.) to which the students turned as a resource. In the presented case the students are referring to a relevant example done by the lecturer in class (segments 1010 and 1011) and it was only towards the end of the engagement that the students turned to the written instruction (segment 1023) where the important point in the procedure was stated explicitly. This observation is supported by the distribution of strategies shown in Table 31 were it can be seen that the strategy of turning to written instructions for a solution is seldom used.

It is proposed that the reason for student S41 using the strategy of announcing that they are “confused” or “not understanding” is because he/she wanted to ensure procedural correctness; something that was regularly observed in engagements of this kind. However, although less evident in the observations, is the possibility that students may engage in such a strategy for reasons other than wanting to “get it right”. For example, contrast S41’s engagement with that of S63 to be seen in segment 1018. S63 is also seeking to engage with the group but he/she does not appear to be particularly concerned with correctness, merely that the procedure should be ‘less arbitrary’.

In segment 1019 there is a reference to the researcher, one of the few occasions in all of the observations when reference was made to the researcher, and it seems that telling the students before they engaged with the apparatus about having to orientate the loop correctly did not really make an impression until they actually saw the need for it from their own experience.

4.2.3 Realisation strategies

The reader is reminded that *realisation* is a process to conceive as real, to bring a formulated physical model into concrete existence, i.e., it is the production of the didactical version of the physical model in the form of a conceptual model.

Having considered the combinations of modelling processes/actions/strategies/reasons shown in Table 30 to Table 35, the dominant strategies and associated reasons with regard to realisation are presented in Table 23.

Table 23: *Realisation*: Salient strategies and reasons for their employment

Student employed the strategy of:
Announcing the result of a calculation (checking the answer).
Presenting a multi-representational solution.
Using data selectively by ignoring readings.
Reason (Strategy was used because the student...)
Wanted to verify the answer.
Wanted to ensure procedural correctness.

The complete list of observable action phrases are tabulated in Table 10, and of these, the dominant observable actions related to realisation were:

i) verifying an answer (calculated or descriptive), and
ii) presenting a solution, showing included/disregarded features.

The reasons for adopting these strategies were generally to present an answer to the problem as was required as part of the weekly problem set, but once again, it was of general concern to the students that they should get the ‘right’ answer which led to the observed verification strategies.

4.2.3.1 Example (1) of strategies in realisation

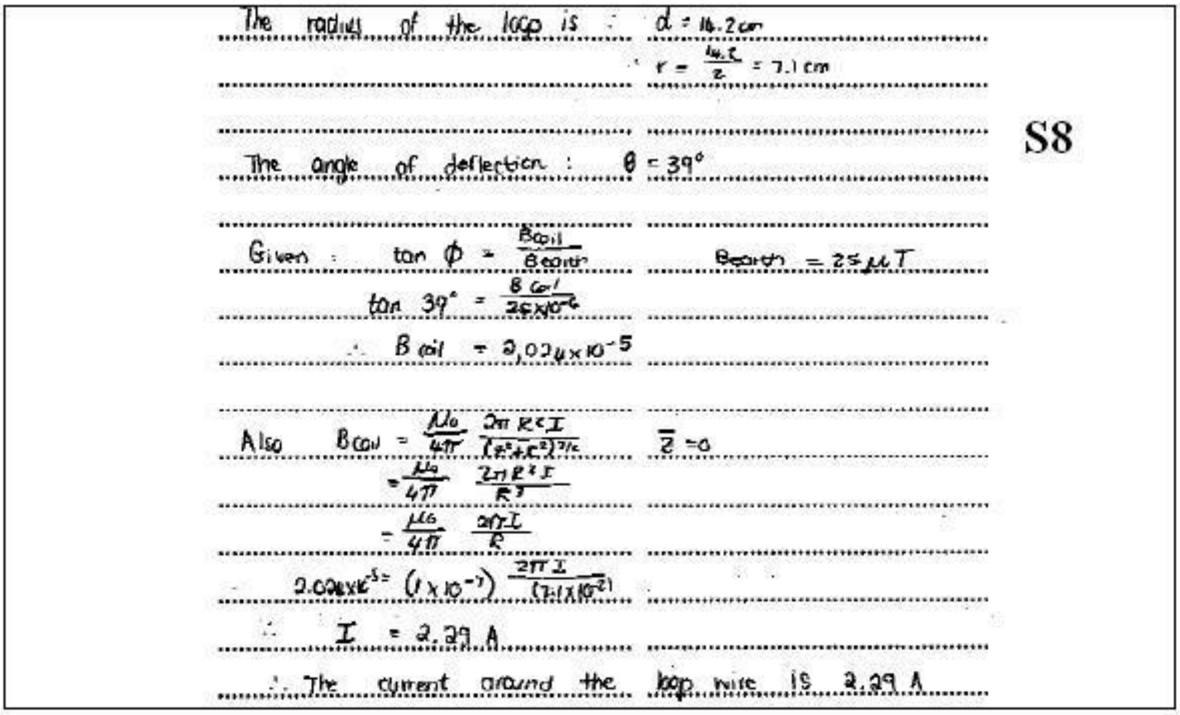
In the majority of observations there is a point at which the students disengage from the apparatus and the group activity resembles a problem-solving mode similar to what has been observed in tutorial work, i.e., students consider the application of the theory, they complete the formulation of the physical model, do calculations and finally write out the answers. During this period students appear to be realising the conceptual model while still formulating the physical model through the modelling processes of application. In this period of the engagement the strategy of announcing and checking their work is most evident. For example:

- In minilab #4, case #2, after students S10 and S15 have completed taking readings of times of rotation and the radius of the wheel, at segment #1314, location #16:06, student S10 turns over the page on which he has written the results of the measurements and says, “Ok, now we can do something”. The two students proceed to work as though they are doing a typical textbook problem to do with the moment of inertia. They talk through the calculations, checking all the while and making corrections as they go, “time is this…”, “yes/no”, “what is the initial ω?” etc., and finally at location #24:40, S10 announces (the answer), “2.5 kg”, to which S15 responds “good”. They immediately change the discussion to something to do with a pending maths test, pack up and leave.
- In minilab #6, case #2, students S8, S43 and S45 take the last reading at location #10:57 and S43 asks, “We don’t know anything else about this do we?” (pointing at the apparatus). They then engage in an activity typical of a tutorial problem-solving session in which they discuss the use of x, y and z axes, equations, constants, etc., constantly announcing and checking one another until at location # 24:35 S43 announces, “I get 2.25”. S45 responds, “It seems ok”. The students immediately change the subject of their discussion, pack up and leave.
- In Minilab #7, case #1, students S4, S20, S22 and S23 engage with the apparatus and just after they have taken the last reading, at location #07:48, they disengage from the apparatus and S23 says, “Time to take the calculators out”; which they all do. A typical period of theoretical problem-solving interaction takes place between the students in which they do calculations and discuss relevant details of the physics problem. They announce and check one another throughout until at location #10:54 S20 announces, “0.225”, to which the others agree. They immediately change the subject to turning off the camera and pack up and leave.

4.2.3.2 Example (2) of strategies in realisation

From the observations made, the majority of written submissions are completed at the time of the engagement with the minilab. This can be seen from the recorded observations of the students writing the answers on the given answer sheet. However, there were some cases where the students took notes on pages other than the answer sheet during the engagement, and while a handful of students consistently made up their own answer sheet, most of the answers were submitted n the given format shown in Figure 23 and Figure 24.

Approximately 50% of the written submissions used multiple representations in as much as they presented their answer with a diagram or a sketch of some sort; the balance used only written answers with calculations. Of interest is that despite the students working very closely together, the preference for including, or not including a sketch does not seems to be influenced by the group in which the students worked. For example, it can be seen from the submissions made by students S8, S43 and S45 who worked together on minilab #6, case #2, are quite different, although they worked closely together.



S8

The radius of the loop is : $d = 16.2\,cm$

$\therefore r = \frac{16.2}{2} = 7.1\,cm$

The angle of deflection : $\theta = 39°$

Given : $\tan\phi = \frac{B_{coil}}{B_{earth}}$ $B_{earth} = 25\,\mu T$

$\tan 39° = \frac{B_{coil}}{25\times10^{-6}}$

$\therefore B_{coil} = 2{,}024\times10^{-5}$

Also $B_{coil} = \frac{\mu_0}{4\pi}\,\frac{2\pi R^2 I}{(z^2+R^2)^{3/2}}$ $z = 0$

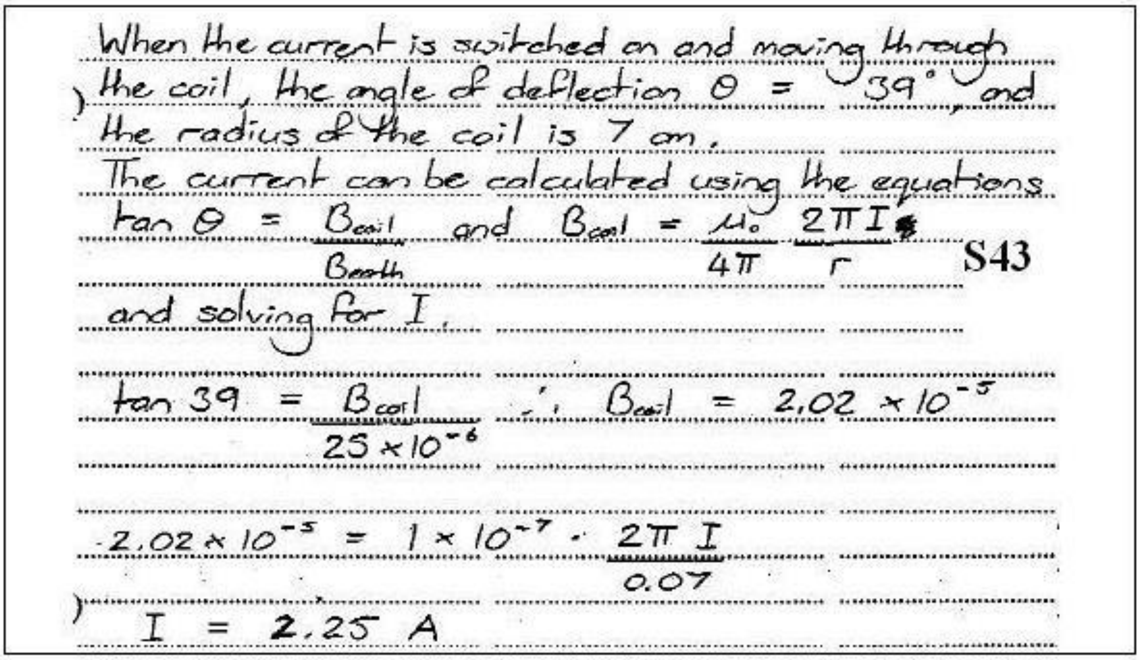
$= \frac{\mu_0}{4\pi}\,\frac{2\pi R^2 I}{R^3}$

$= \frac{\mu_0}{4\pi}\,\frac{2\pi I}{R}$

$2.024\times10^{-5} = (1\times10^{-7})\,\frac{2\pi I}{(7.1\times10^{-2})}$

$\therefore I = 2.29\,A$

$\therefore$ The current around the loop wire is 2.29 A



When the current is switched on and moving through the coil, the angle of deflection θ = 39°, and the radius of the coil is 7 cm.

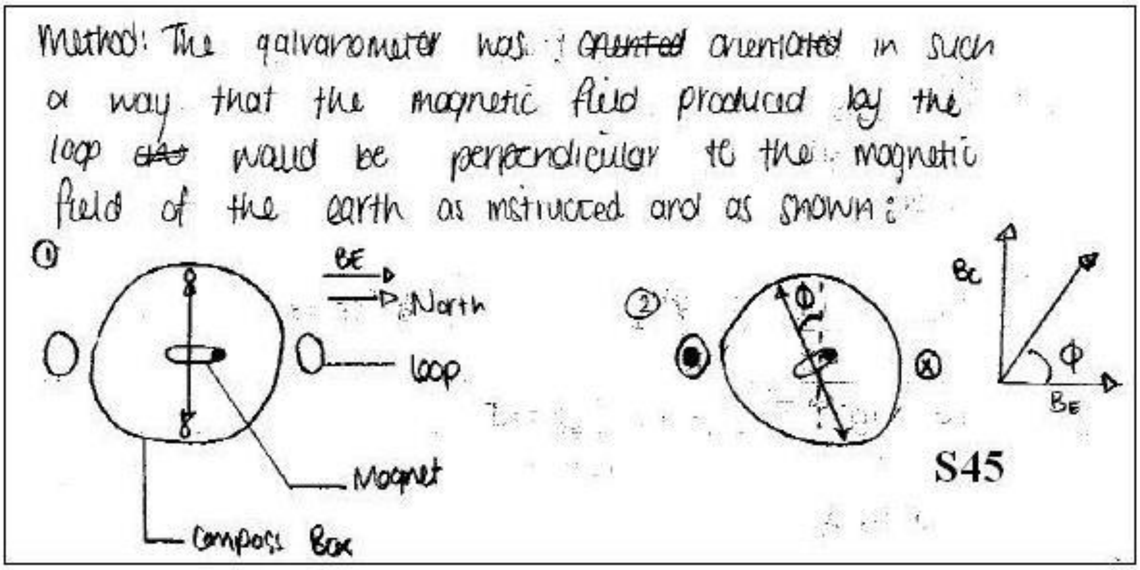
The current can be calculated using the equations $\tan\theta = \frac{B_{coil}}{B_{earth}}$ and $B_{coil} = \frac{\mu_0}{4\pi}\frac{2\pi I}{r}$ and solving for I.

$\tan 39 = \frac{B_{coil}}{25\times10^{-6}}$ ∴ $B_{coil} = 2{,}02\times10^{-5}$

$2{,}02\times10^{-5} = 1\times10^{-7}\cdot\frac{2\pi I}{0.07}$

$I = 2{,}25$ A

S43



Method: The galvanometer was ~~orented~~ orientated in such a way that the magnetic field produced by the loop ~~[illegible]~~ would be perpendicular to the magnetic field of the earth as instructed and as shown:

S45

Figure 29: Examples of students' realised models

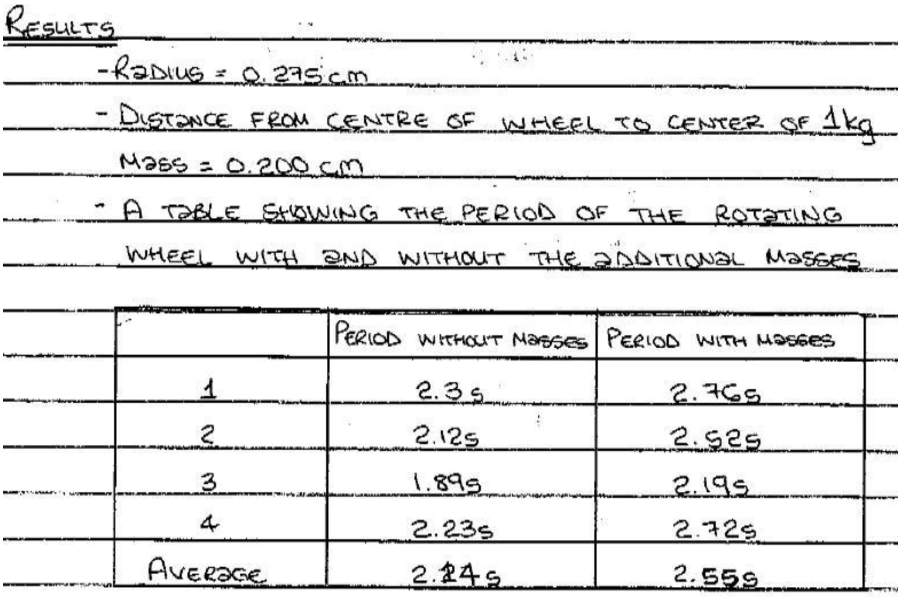
4.2.3.3 Example (3) of strategies in realisation

There are noted examples in the data where students have been observed to have written down some or other value for a variable when they engaged with the apparatus, but in their written work they have presented some different values. An example is give here, and while this is a strategy not used often, it speaks to the way in which students may regard the relevance of the actual data as opposed to data that is made up; something that is explored in the ‘thick’ description of the findings in 4.4 below.

In minilab #4, conservation of angular momentum, students had to determine the angular speed before and after the masses had been dropped onto the turning wheel but the wheel was certainly not friction free, it slowed down noticeably therefore making it difficult to time some number of turns before and after the dropping of the masses. The other relevant measurand was the radius of gyration of the applied masses.

> In minilab #4, case #1, at location #23:44, students S9 and S59 are seen recording time readings for 10 rotations before dropping the masses and 10 rotations after. Immediately after that, at location #24:45, student S9 uses a metre stick to record the distances of the masses from the centre shaft, “… *should be* 14.5 (cm),” she says. This was followed, at location #25:30, by S9 reading out and writing down the pairs of recorded times for ten rotations before and ten rotations after dropping the masses onto the wheel, “28.42, 24.97; 31.61, 28.65; 25.46, 22.41; 29.51, 26.54; 22.62, 20.63; 18.16, 16.24”.

However, S9’s results are shown in the written submission in Figure 30.



RESULTS

- RADIUS = 0.275 cm
- DISTANCE FROM CENTRE OF WHEEL TO CENTER OF 1kg MASS = 0.200 cm
- A TABLE SHOWING THE PERIOD OF THE ROTATING WHEEL WITH AND WITHOUT THE ADDITIONAL MASSES

	PERIOD WITHOUT MASSES	PERIOD WITH MASSES
1	2.3 s	2.76s
2	2.12s	2.52s
3	1.89s	2.19s
4	2.23s	2.72s
AVERAGE	2.14 s	2.55s

Figure 30: Example of students’ written submission presenting results

It can be seen that not only do the periods calculated from the reading recorded at the time of observation not match those in the written submission, but the radius of gyration that was observed to be recorded as 14.5 (cm) is presented as 0.200 m (recorded as 0.200 cm) in the written submission.

Furthermore, there is no suggestion that students S9 and S59 had repeated their engagement with minilab #4 at some other time, nor did S59 make any reference to their repeating the engagement when this minilab was discussed during the end-of-year interview.

Why the students may use ‘other’ data, which they presumably consider to be better than what they had collected, is not clear. What is evident from the data is that students will occasionally use a strategy of reporting data that comes from a fictitious source, a pseudo-world, rather than the real world that they themselves have observed and aspects of which they have measured.

4.2.4 Idealisation strategies

The reader is reminded that *idealisation* is the process to abstract, in the sense of “taking out” (choosing), those features of a real world system considered relevant to the formulation of a particular physical model, and by implication ignoring features considered irrelevant to the physical model. The purpose for idealising some real world situation is so that the idealised features may be incorporated into a physical model. It is also possible that in the process of idealisation, the descriptions of idealised features may be distorted.

Having considered the combinations of modelling processes/actions/strategies/reasons shown in Table 30 to Table 35, the dominant strategies and associated reasons with regard to idealisation are presented in Table 24.

Table 24: *Idealisation*: Salient strategies and reasons for their employment

Student employed the strategy of:
Itemising (verbally) variables in a formula, and then deciding from that list which aspects of the apparatus should be idealised and so are

included in the physical model.
Announcing an observation (of something that may have been noticed), and then waiting for a response from the group to see if it should be idealised so that it could be included in the solution.
Adopting a 'null' solution to a problem/situation.
Letting a particular student take on the 'expert' role.
Reason (Strategy was used because the student...)
Wanted to ensure procedural correctness.
Was responding to a lead by other/s.

The complete list of observable action phrases are tabulated in Table 10, and of these, the dominant observable actions related to idealisation were:

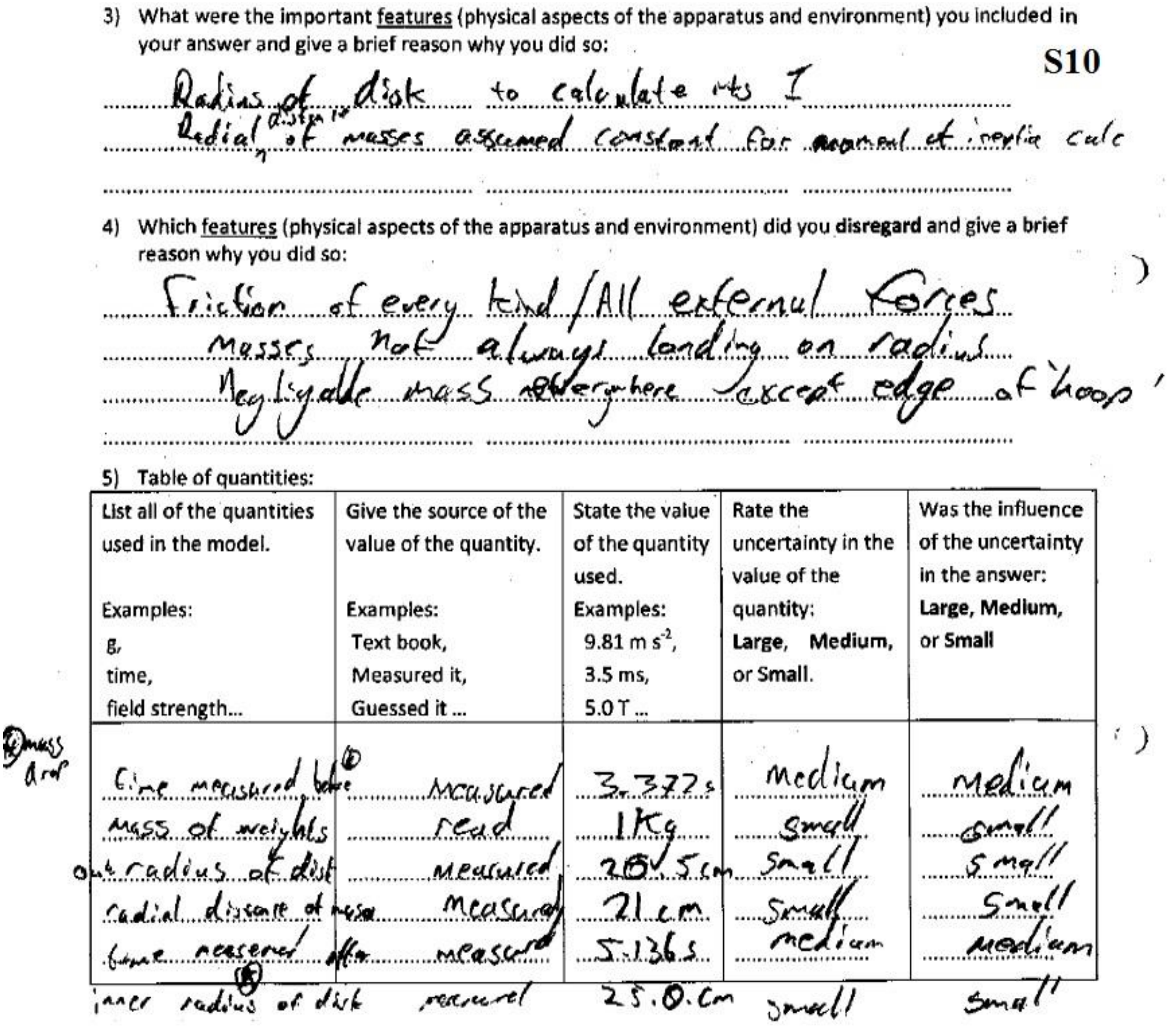
i) the observations students make as they examine the apparatus,
ii) the identification of procedures or variables, and
iii) what the students chose to measure and what to ignore.

The reasons for adopting these strategies were generally to foster a method or a procedure and once again the students took due care to ensure procedural correctness. However, when it came to why students would defer to any particular student as the ‘expert’, there was often no clear reason as to why that student in particular. In a later section in this chapter further findings on the ‘expert’ role will be presented.

4.2.4.1 Example (1) of strategies of idealisation

In the following example the strategy of idealising what is itemised in a particularised formula is illustrated along with the strategy of having the formula drive how the idealisation is done, rather than the student looking at the object being idealised and selecting a formula to suit. In this example, from minilab #4, case #2, students S10 and S15 have to idealise the features of the wheel so as to model the moment of inertia of the wheel. As can be seen from Figure 31, the hub of the wheel is quite substantial and there is a cardboard disk covering the spokes of the wheel. The cardboard is there to prevent the weights from falling through to the table. The relevant observed sequence is shown in Table 25 and the answer sheet that student S10 was filling in while the discussion was taking place is shown in Figure 32 and Figure 33.

Figure 31: Student S10 reading the radius of the wheel



3) What were the important features (physical aspects of the apparatus and environment) you included in your answer and give a brief reason why you did so:

S10

Radius of disk to calculate its I

Radial distance of masses assumed constant for moment of inertia calc

4) Which features (physical aspects of the apparatus and environment) did you **disregard** and give a brief reason why you did so:

Friction of every kind / All external forces

Masses not always landing on radius

Negligible mass everywhere except edge of hoop

5) Table of quantities:

List all of the quantities used in the model. Examples: g, time, field strength...	Give the source of the value of the quantity. Examples: Text book, Measured it, Guessed it ...	State the value of the quantity used. Examples: $9.81\ m\ s^{-2}$, 3.5 ms, 5.0 T ...	Rate the uncertainty in the value of the quantity: **Large**, **Medium**, or **Small**.	Was the influence of the uncertainty in the answer: **Large, Medium,** or **Small**
① mass drop time measured before ①	measured	3.372s	medium	medium
mass of weights	read	1Kg	small	small
outer radius of disk	measured	26.5cm	small	small
radial distance of mass	measured	21 cm	small	small
time measured after ②	measured	5.136 s	medium	medium
inner radius of disk	measured	25.0 cm	small	small

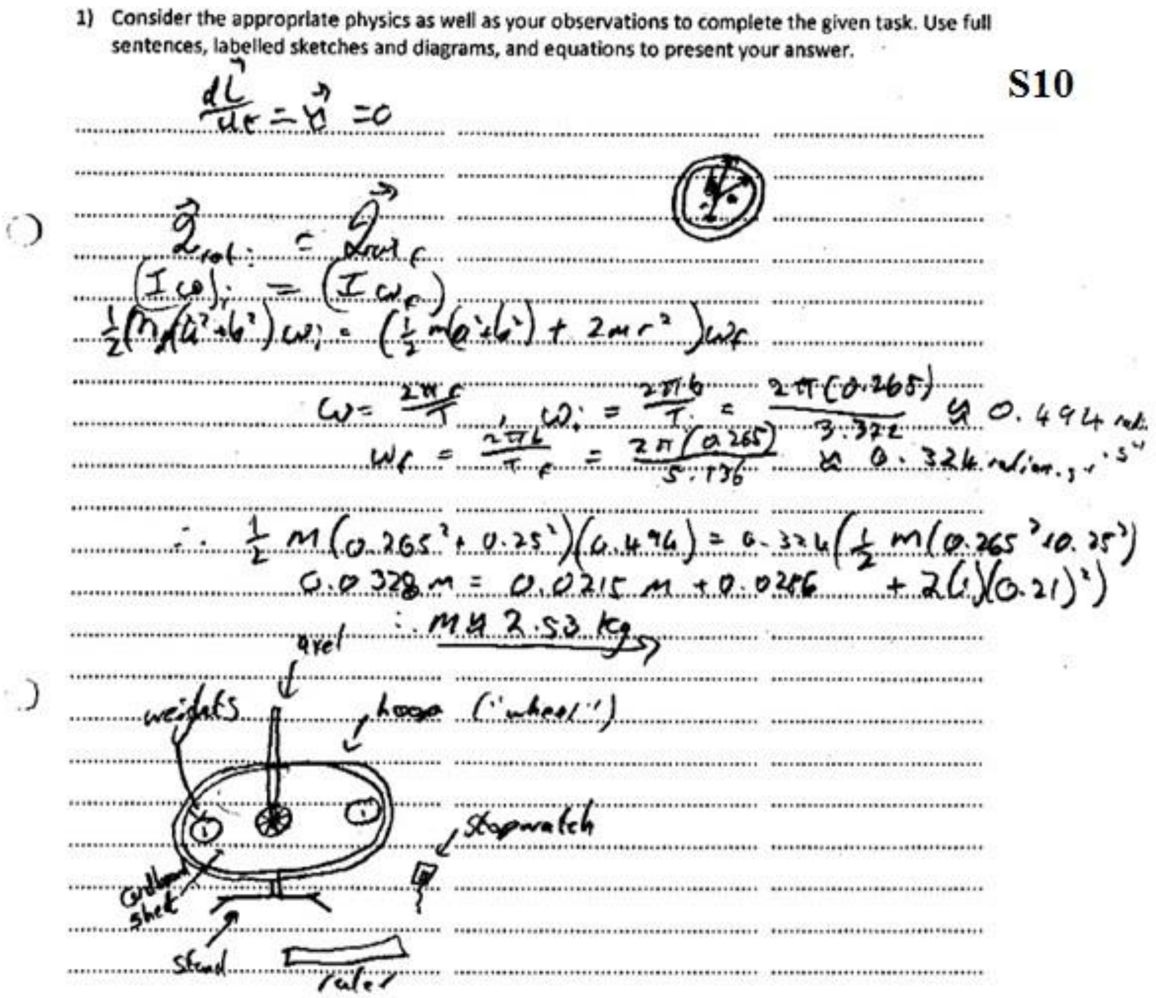
Figure 32: Answer sheet showing written submission of idealisations made

Table 25: Example to illustrate student idealisation driven by itemising variables

Segment #	location #	Student S#	***Note on context (in italics)* and "Transcript" or written response**	**Researcher's memo**
1283	02:30	15	We are not using 'g', what constants are we using, if any?	S15 is reading from the prompt on the answer sheet.
1284	02:36	10	Ah, none. I guess we are using time, mass (points at the wheel), mass of weights, radius of disk, radial distance of masses…, I guess we should include here 'mass is not always landing on radius’.	As S10 itemises these variables, both students write them down on the answer sheet.
1285	05:25	15	*After the two students have quantified the time they come to quantifying the features of the wheel,* Radius of disk.	A short period of calculation and discussion about the measured times follows before they turn their attention back to the features of the wheel.
1286	05:30	10	*S10 picks up the metre stick and takes a reading from approximately the centre of the axle to the outside of the wheel,* Mmm, 26.5 (cm).	S10 has ignored the other features of the wheel. See Figure 31.
1287	05:40	15	Did you measure it from the centre (of the axle)?	S15 also looks at the metre stick and the way in which the reading was taken.
1288	05:45	10	We are just going to make the simplifying assumption that this is… hey! Is this a hoop or a disk?	It is not known what prompted this question.
1289	05:49	15	Do hoops change things?	
1290	05:50	10	Yes, it has a different moment of inertia.	S10 has particularised a formula for later use.
1291	05:56	15	This may be a hoop, what does it (question sheet) say…, a wheel. I would say it is a hoop.	S15 looks to the answer sheet for clarity on the description of the wheel
1292	06:02	10	Ok so then we need to…	S10 turned his attention to the pages on the table.
1293	06:04	15	Do you have the formula sheet?	Of the moments of inertia of different regular shapes.
1294	06:09	10	*Looks at the papers in front of him,* Ja but it doesn't have it (the appropriate formula).	S10 is looking for a formula for the moment of inertia for a hoop.
1295	06:12	15	Aah…, (shall we make a) simplifying assumption, disk? (Laughs.)	S15 proposes the idealisation of a disk.
1296	06:14	10	Dude, a disk with uniformly distributed mass? I don't think we can pull that one.	S10 appears to take cognisance of the complexity of the object.
1297	06:25	10	*Writing,* Negligible mass everywhere except edge of hoop.	S10 write this down as he dictates.
1298	07:28	10	*An unconnected discussion about programming follows before the students return to the topic of the radius of the wheel.* So the radius of the disc, what did you say?	
1299	07:30	15	You said 26, and I said 25, so let's go 25.5 (cm)	Students are still writing down the values used in the Table of quantities, question 5 of the answer sheet. See Figure 32.

1300	09:38	10	*S10 has gone out of the room for a while to see if he could find out what the moment of inertia of a hoop was but returns without finding anyone who could help them*. I don't know, (looking under the cardboard covering) it has spokes so we can't really call it a disk.	S10 is still focussed on the formula for the moment of inertia of a hoop, but is looking at the structure of the wheel.
1301	09:45	15	Let's google it (Takes out his cell phone and does an internet search).	S15 tries various options, Wikipedia, etc.
1302	12:20	15	*After a search*. Disk with a hole…, apparently it is $1/2m(a^2 + b^2)$.	S15 announces the result of the search.
1303	12:24	15	Where I assume a^2 (*sic*) is from there to there (axle to inner ring), and b^2 (*sic*) is from there to there (axle to outer ring).	S15 looks at the picture on the cell phone and then at the wheel.
1304	12:30	10	I think a^2 (*sic*) is there to there (inner ring to inside of outer ring) and b^2 is there to there (inner ring to outside of outer ring).	S10 repeats the exercise but interprets it differently.
1305	14:07	15	*After some discussion about where to measure and how to use the metre stick S15 points to the inner ring and says*, *b* is here.	S15 repeats the statement made in ref #1303 above.
1306	14:09	10	No, there is no mass between here and here (the inner ring and the inside of the outer ring), we are just ignoring this completely (places his hand on the hub of the wheel).	S10 makes a statement about the idealisation of the inner mass.
1307	14:53	10	*After a further discussion about the markings on the metre stick and where the readings should be taken, S10 places the metre stick on the wheel and says*, So that makes it 26.5 (cm).	There appears to be some confusion about the detail of where to measure which is interpreted as a problem of approximation.
1308	14:55	15	Ok, I didn't line it up with the middle, I just put it there (points to the edge of the inner ring).	S15 again refers to the inner ring which he has not ignored, see ref #1303 and #1305.
1309	15:00	10	No, there is nothing to measure there. (Points to the inner ring). We need here and here (points to the outer ring)..., look at the picture (points to the image on the cell phone) that's where the mass is.	Students appear to be fitting the wheel to the image of the idealised hoop on the screen of the cell phone.
1310	15:10	15	Look, *b* is the distance from the centre to the start of the mass which starts here (points to the inner ring).	Students are both looking at the picture on the cell phone and identifying the dimensions of *a* and *b* from the picture.
1311	15:14	10	There is nothing, look under here (the cardboard covering) just spokes.	S15 has not looked under the cardboard covering until now.
1312	15:25	15	What are we measuring? Are we measuring this thing? (points at the outer ring). Oh, I see now.	S10 says yes" and shows by hand the two dimensions from the axel to the inner side and then the outer side of the outer ring.
1313	15:33	10	Ok (reading off the metre stick) 25 to 26.5 (cm).	S15 responds "ja".
1314	16:00	10	*After making a sketch on the answer sheet*, uncertainty is small.	S15 responds "ja". Students then disengage with the apparatus and begin the calculate the answer.

In the written submission by student S10 the relevant dimensions *a* and *b* are shown and while there is a suggestion of an inner ring in the sketch, there is no suggestion that there was a substantial hub to the wheel. See Figure 33.



1) Consider the appropriate physics as well as your observations to complete the given task. Use full sentences, labelled sketches and diagrams, and equations to present your answer.

S10

$\frac{d\vec{L}}{dt} = \vec{\tau} = 0$

$\vec{L}_{rot\,i} = \vec{L}_{rot\,f}$

$(I\omega)_i = (I\omega_f)$

$\frac{1}{2}(m(a^2+b^2))\omega_i = (\frac{1}{2}m(a^2+b^2) + 2mr^2)\omega_f$

$\omega = \frac{2\pi f}{T}$, $\omega_i = \frac{2\pi b}{T_i} = \frac{2\pi(0.265)}{3.372} \approx 0.494$ rad

$\omega_f = \frac{2\pi b}{T_f} = \frac{2\pi(0.265)}{5.136} \approx 0.324$ rad/s

$\therefore \frac{1}{2}m(0.265^2+0.25^2)(0.494) = 0.324(\frac{1}{2}m(0.265^2+0.25^2) + 2(1)(0.21)^2)$

$0.0328m = 0.0215m + 0.0286$

$\therefore m \approx 2.53$ kg

Figure 33: Answer sheet showing S10's submitted calculations

During the subsequent interview, while the interviewer and S10 were watching the sequence in Table 25, the interviewer stopped the recording just after segment #1309 and the following conversation took place:

18:10	I:	(Referring to segment #1309) You said to him (S15), "look at the picture" and he picked up his cell phone, what was he looking at?
18:15	S10:	We weren't sure about this $1/2m(a^2 + b^2)$ business [points at his written submission in front of him], and we looked it up on the internet and it came with a nice picture. I don't know if that is considered cheating…
18:35	I:	No, that was a perfectly legitimate strategy.
18:38	S10:	When we looked it up, the picture sort of…, because there was confusion about

what that inner ring was [points at the image on the screen], whether we should use it at all…

18:45 S10: Sounds like I was pretty determined that we don't use that (the inner ring) at all. And I don't think I did in the end.

18:52 I: Although you did use *a* and *b* here [pointing at the answer sheet].

18:55 S10: I was insisting that that would be to the inside of the rim and to the outside (of the rim) and I am not sure what he (S15) wanted.

19:05 S10: But then the point was that we had looked it up to check the formula, and there was a picture, and then, when this argument came about, we just checked the picture to see exactly what the *a*s and *b*s related to.

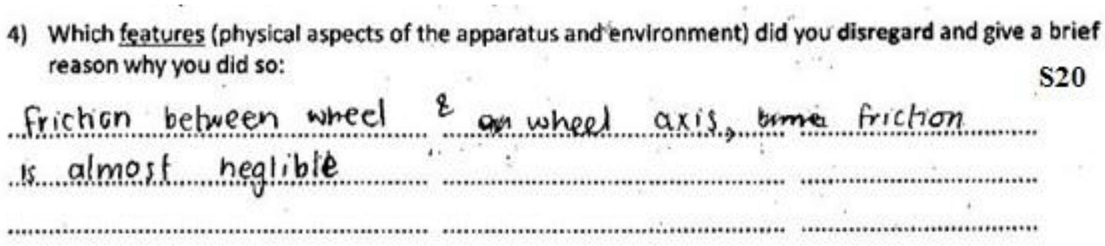
Of relevance here is that the students did not look at the features of the wheel and consciously decide that the hub would have a negligible effect and in the case of student S15, there was never a sense that he was looking at the wheel and then idealising the features of the wheel to be incorporated into the physical model, but that he was looking at the particularised formula and finding corresponding features in the wheel to match the variables itemised in the formula.

4.2.4.2 Example (2) of strategies in idealisation

In this example the student strategies in idealising the friction of a wheel turning on its axle are presented. In this case the students idealise a property of the apparatus to zero not because they consider it negligible, but because they do not know what else to do, i.e., they recognise the relevant feature, but adopt the strategy of a "null" solution.

As has been noted previously, in minilab #4, conservation of angular momentum, students had to determine the angular speed of a wheel that was turning freely on is axle. Problems similar to the one presented in this minilab had been done in lectures and there are well-worked examples in the text book, *Matter & Interactions,* 3rd ed., p. 459, so the students had a good selection of theoretical examples to use as a guide. However, unlike the theoretical cases in the textbook and lectures, the friction between the axle and the wheel was not negligible as it was quite obvious that the wheel was slowing down.

In the written response to minilab #4, question 4, student S20 made the following submission:



4) Which features (physical aspects of the apparatus and environment) did you disregard and give a brief reason why you did so:

S20

friction between wheel & ~~on~~ wheel axis, ~~time~~ friction is almost neglible

However, in the interview with S20, after the student had given a good explanation of how they had to spin the wheel fast enough to take the readings before it had stopped, while at the same time if the wheel spun too fast the masses would fly off; at location #36:00 the interviewer drew S20's attention to the fact that, "friction is almost negligible" had been written in the submission.

36:00 I: You had written [pointing to the written text] that friction was almost negligible.

36:03 S20: But it (friction) wasn't really, it was quite substantial [laughs].

36:07 S20: I don't actually know why I wrote that.

Student gives a brief description of how the members of the group went about doing the write-ups, often in a hurry on the day before the hand-in time, perhaps suggesting that they did not have time to think through the problem. Then the interviewer returns to the subject by making a suggestion.

37:03 I: Do you think it is possible that you ignored friction because it is always ignored?

37:10 S20: It was a thought, because even when (the lecturer) was demonstrating the conservation of momentum with the air track, there was friction in that one and (the lecturer) said "ok, we will just ignore it".

37:28 S20: And in all of our practicals, with movement [gesticulates showing movement], there was friction, and we ignored that; it was almost negligible.

37:31 S20: So although it (friction) was there… [waves hand back and forth] we knew it was there…, we knew it was a problem…, we needed to get past [gesticulates to indicate going round].

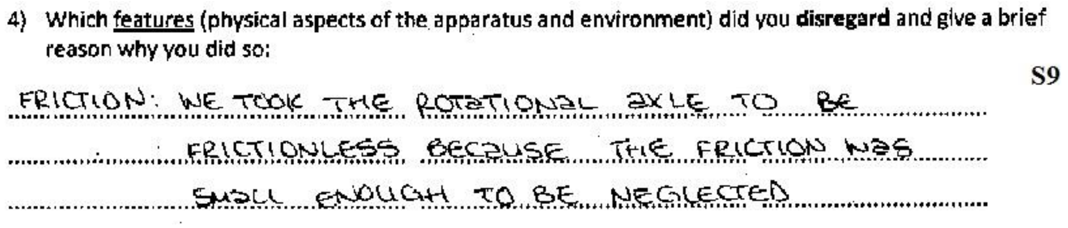
37:40 S20: Also I think…, we didn't actually know how to work it out…, which is another reason why we didn't...

38:00 S20: For me, it was always a very sketchy area how to work it (friction) out.

The response by S20 to the question of friction in the wheel is typical of the majority of written submissions and there is evidence to suggest that students were predisposed to the notion that the wheel was friction free. For example:

> In the observation of minilab #4, case #1, at segment # 417, location #12:37, student S9 has spun the wheel and without looking at the wheel says, “this (points to the wheel) is going to carry on spinning for as long as we leave it”, implying that the wheel is friction free. Later, having engaged with the spinning wheel for a while, at segment #426, location #13:35, S9 says, “we assume this (points at the hub of the wheel) is a frictionless surface”. And at the end of the engagement, at segment #464, location #26:40, S59 says, “Just from this, (looking at the time readings), it is clear that this frictionless scene (does inverted commas by hand) isn't so frictionless”.

Student S9’s written submission suggests that the question of friction in the wheel had been noticed and this is borne out by S9’s written submission:

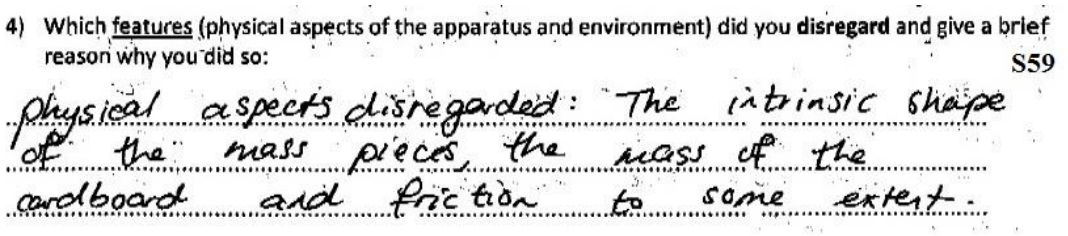


4) Which **features** (physical aspects of the apparatus and environment) did you **disregard** and give a brief reason why you did so:

S9

FRICTION: WE TOOK THE ROTATIONAL AXLE TO BE
FRICTIONLESS BECAUSE THE FRICTION WAS
SMALL ENOUGH TO BE NEGLECTED

That the question of what to do with the observed friction was difficult is illustrated by the response by student S59 for example, who had made the following written submission:



4) Which **features** (physical aspects of the apparatus and environment) did you **disregard** and give a brief reason why you did so:

S59

physical aspects disregarded: The intrinsic shape
of the mass pieces, the mass of the
cardboard and friction to some extent.

Student S59 was the partner to S9 and in the subsequent interview and after having watched a replay of the observed interaction referred to above, the interviewer invited S59 to speak about their observation of the friction in the wheel:

09:10 I: Do you remember any of that? (Of the interaction between S9 and S59).

09:16 S59: I was really struggling with that in my mind because I thought the wheel…, 'cos it was assumed to be frictionless (and we saw) it was not absolutely frictionless, it would actually slow down and then if you put the masses on top it would slow even more.

It is of significance that the students' use of the strategy of a "null" solution was not necessarily because they had consciously idealised the phenomenon in question, but because they did not know what to do with what they had observed. When stating that they had ignored the friction in the wheel they would often add a rider to the effect that it "complicated things too much" (S6), or "was impossible to calculate" (S41).

4.2.4.3 Example (3) of strategies in idealisation

In this example the strategy of letting a student take on the 'expert' role in idealising the spatial change of a magnetic field produced by a moving permanent magnet is presented.

In minilab #7, Faraday's Law, students had to engage with a notoriously difficult concept, that of a changing magnetic flux with respect to time,

$$\frac{d\Phi}{dt} = \frac{d(\boldsymbol{B}.\boldsymbol{A})}{dt}.$$

Of relevance here is that the flux depends not only on the rate of change of the magnitudes of ***B*** and ***A***, but also on their spatial orientation, i.e., the dot product of the two vectors ***B*** and ***A***. And when the permanent magnet is being withdrawn from the solenoid, not only is the magnitude of the magnetic field changing at each cross-section through the solenoid, but the direction of the magnetic field with respect to the area at that cross-section is also changing. So, although the cross-sectional area,

A, is the same for every loop, the value of d***B***/dt for each loop is not. This suggests that the change in flux with respect to time, $d\Phi/dt$, is not the same for every loop throughout the solenoid – meaning that each turn does not contribute equally to the induced *emf* in the solenoid at any instant.

It was recognised that this is a difficult phenomenon to idealise and as was expected, all of the students presented an answer that suggested that they had assumed that the contribution to the total induced *emf*, of each turn in the solenoid, was equal; thereby implying the idealisation that $d\Phi/dt$ at each cross-section of the solenoid was the same. So, in an effort to probe this aspect of the modelling, when an academically strong group of students (including student S24) agreed to have their engagement with minilab #7 recorded, they were primed by the researcher by asking them to consider carefully whether the contribution of every loop to the total induced *emf* would be the same. The student engagement is presented in Table 26.

Table 26: Example to illustrate student's 'expert' role in idealisation

Segment #	location #	Student S#	***Note on context (in italics)*** **and "Transcript" or written response**	**Researcher's memo**
1075	10:55	63	What is…, is *N* the number of coils (turns)?	S63 is looking at the formula for Faraday's Law on the page in front of him.
1076	11:03	24	(Yes) the number of turns…, but that would be the entire number of turns in the solenoid. (shows the whole solenoid by hand).	S24 is responding to S63's wanting to know if *N*, in the formula, represented the number of turns.
1077	11:23	7	How far down do these coils (turns) go (shows by hand the length of the coil)	S7 responding to S24's suggestion that the number *N* may be the entire set of turns in the coil.
1078	12:15	24	I mean, the magnetic field is changing throughout this thing (gestures by hand)…, (pauses). So actually, I think that that would then be all of them (the turns). You keep the cross-sectional area the same so we would have to measure the length (gestures again). *Here follows a silent pause while S24 appears to be thinking deeply, the other three members of the group appear to be waiting, just looking at S24 in silence, then S24 continues.*	S24 seemed to have concentrated intensely on this this problem for a few minutes and has finally decided on a solution. It must be said that this problem had been highlighted to this student before he engaged in the minilab as it is a particularly difficult one.
1079	12:28	24	(The length is) probably from there (points) to there (points).	S63 has picked up a ruler and is measuring the length of the coil.

1080	12:35	24	Presumably $d\mathbf{B}/dt$ is the same everywhere here as we move the magnet (gestures all along the coil), so if (inaudible) in a little cross-section over there it is going to induce a current and in there as well, by the same amount, because $d\mathbf{B}/dt$ will be the same everywhere so *N* is just the amount of turns in the whole thing and ***A*** will just be the cross-sectional area. *The rest of the group appear to accept this reasoning without hesitation.*	S24 gives a 'judgement' on why he believes *N* is all the turns in the coil. This view is not quite correct in that $d\mathbf{B}/dt$ is not the same everywhere - ***B*** changes direction and strength as one moves away from the magnet - but it nevertheless exhibits a strategy that draws on a logic that is derived from the equation.

Just prior to this interaction, the question of whether all the turns contributed equally to the induced *emf* had been raised within the group, which led to S63 asking if *N* represented the number of turns. S24 then reasons out aloud as the rest of the group just listens without contributing. The fact that the rest of the group accept this reasoning without hesitation suggests that they appear to have adopted the strategy of letting student S24 take on the ‘expert’ role. In the subsequent interview (recording S24A), at location #31:20, S24 confirmed that he was still of the opinion that the change in the vertical component of the magnetic field was the same everywhere, i.e., he confirmed his original reasoning.

It is of relevance that in almost all of the observations of the student engagements, it is not clear that the students expressly considered that there was a need to idealise something. It appears that most students simply looked at the formula which was in the form,

$$emf = -N\mathbf{A}.\frac{d\mathbf{B}}{dt},$$

and used the strategy of itemising variables, which led to action of observing, which in turn led to the determination of the total number of turns, *N*, a number that was subsequently used in the formula without further consideration.

4.2.5 Approximation strategies

The reader is reminded that *approximation* is a process by which one approaches what may be thought of as a ‘correct’ estimate, concept, of a given quantity or quality. It is to simplify the description of the observed physical system in order to give a description that is not exact, but is tractable and considered ‘close enough’ to the real world phenomenon in question.

Having considered the combinations of modelling processes/actions/strategies/reasons shown in Table 30 to Table 35, the dominant strategies and associated reasons with regard to approximation are presented in Table 27.

Table 27: *Approximation*: Salient strategies and reasons for their employment

Student employed the strategy of:
Itemising (verbally) step/s in a procedure (to measure something).
Announcing the prediction of the outcome of an action.
Announcing a value of a reading taken.
Checking on feasibility of a measured value.
Letting a particular student take on the 'expert' role.
Attempting uncertainty reduction by taking multiple readings or setting the apparatus to ‘zero’.
Reason (Strategy was used because the student...)
Wanted to ensure procedural correctness.
Was responding to a lead by other/s.
Wanted to simplify the task (make easier).

The complete list of observable action phrases are tabulated in Table 10, and of these, the dominant observable actions related to approximation were:

i) the observations made by the students as they examined the apparatus,
ii) taking action, i.e., ‘doing’ by carrying out a procedure,
iii) measuring, including the assessment of uncertainty, and
iv) confirming a measurement or a value.

The students took due care to ensure procedural correctness. However, as before, there was often no clear reason as to why a particular student was allowed to take on the ‘expert’ role.

4.2.5.1 Example (1) of strategies in approximation

In the context of this study, the strategies of approximation are considered not only in the sense of the cognitive process of narrowly ‘approximating a value’ in numerical terms, but in the broader sense that an experimental procedure has to be devised and sometimes the operation of the measuring instrument has to be figured out in order for the student to take meaningful readings and to evaluate the uncertainties associated with those measurements.

In this example the student strategies in approximating the extension of the stretched length of wire in minilab #2, interatomic spring constant, are presented[9]. When approximating the variables to be quantified in this minilab, students had to contend with the facts that:

a) it was not possible, with the naked eye, to see the wire stretch,
b) the image of the wire as seen through the microscope was inverted so its apparent movement was in the direction opposite to what was expected,
c) students had to work out a measurement procedure, and
d) reading the vernier scale on the travelling microscope had to be learned.

In the lengthy example presented in Table 28, three students engage with all four of these problems at the same time. Directly after the presentation of the table, the threads showing the use of the strategies are presented so going directly to the exposition and then referring back to the details in the table can be done without loss of continuity in the reading.

Table 28: Example to illustrate a multi-level student engagement with approximation

Segment #	location #	Student S#	***Note on context (in italics)* and "Transcript" or written response**	**Researcher's memo**
212	05:32	65	*S14 had lined up the microscope with the cross-hairs on the edge of the paper marker on the wire. S65 looks into the microscope for the first time*. How do we know if it is stretched? *Neither of the two group members give him an answer.*	(Ref Inc #204) Student S65 appears to have a reservation as to whether it is possible to measure the stretching of the wire.
213	05:50	14	*S14 has added a mass to the apparatus*. Did it move? I had put it (the crosshairs) right at the edge of the page (the paper marker).	S14 has added a 1 kg mass to stretch the wire while S65 is looking through the microscope.

---

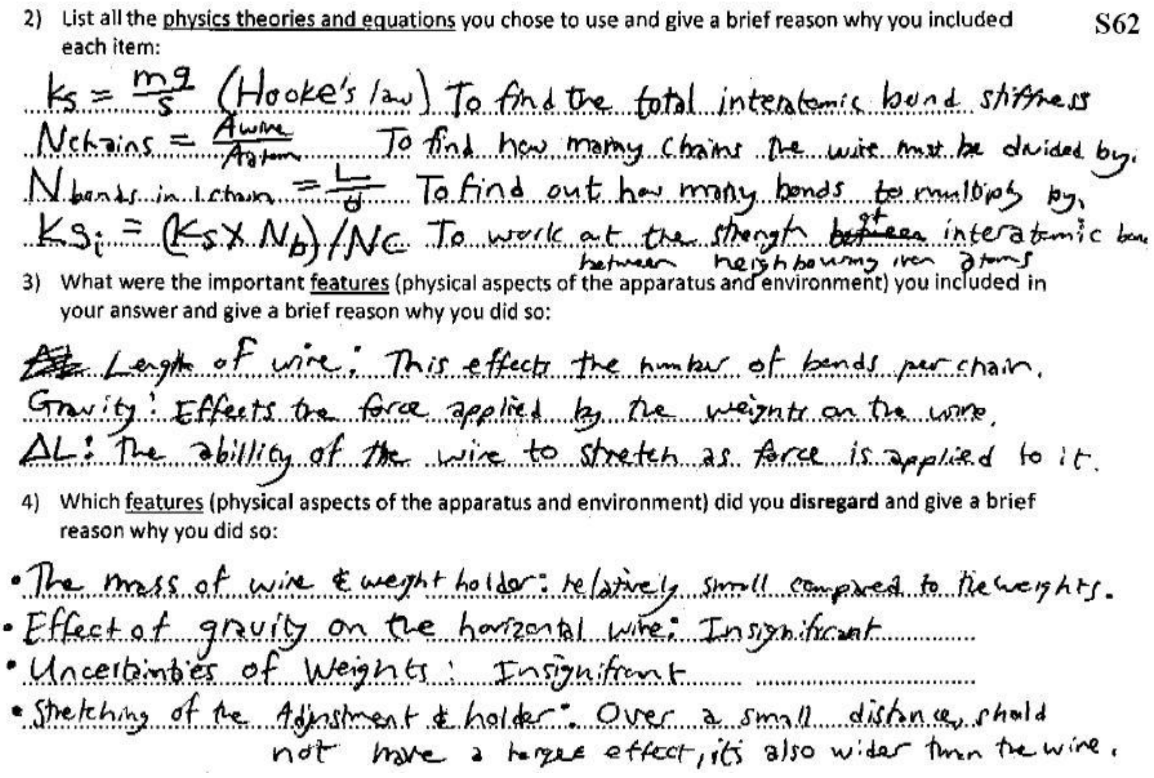
[9] The textbook solution to this problem (*Matter & Interactions* p. 145) proposes the idealisation that the interatomic structure of a length of drawn iron wire may be modelled as multiple, regular chains of ball-and-springs. There is no evidence in the observations or submissions that students queried the validity of this model.

214	05:55	65	*S65 Suggesting a different method of lining the tape marker up with the crosshair*. You should put it at the centre of the target (ref. #217).	One of the confusing aspects of using the travelling microscope is that the direction moved is inverted, i.e. visually in the opposite direction to the actual movement.
215	06:00	14	*S14 ignoring S65's suggestion that the apparatus should be set with the crosshair at the centre of the tape marker*. Ja but how much did it move?	S14 gets no response from S65 to his question.
216	06:15	14	*S14 Resorts to making a sketch in order to illustrate what he has done*. Here is the wire, here is the page (paper marker), I put it here… (Making a sketch on a separate piece of paper).	This may be thought of as a sub-set of **realising** the solution.
217	06:30	65	*S65 repeats his suggestion regarding the reference point*. We should put it at the centre of the target (ref. #214).	S65 Does not seem to realise that a sharp edge is required to be used as a reference.
218	06:35	14	But then we won't know how much it has moved. If you do that how will you know?	S14 appears to explain the choice of the edge of the paper as a reference.
219	06:40	65	Ja…, whatever you say.	S65 Agrees to go along with the explanation by S14 but does not seem convinced.
220	06:50	62	*S62 seeks to join the engagement.* How are you guys doing this? (setting up the travelling microscope).	S62 has remained out of the discussion about the travelling microscope up and until this point.
221	06:53	65	*S65 replies directly in regard to how to use the travelling microscope*. I have no idea.	S65 in response to S62 declares that he does not know. (Ref Inc # 219).
222	06:55	14	*S14 has taken charge and gives a confident explanation*. Look here (beckons for S62 to come closer) and to look into the microscope. Can you see the edge of the page (paper marker)?	S14 has established himself as the group leader.
223	07:05	14	*S14 continues to give a clear explanation of what is being seen through the microscope*. Here is the paper (shows on the sketch he has made) I initially put it here, and as you can see now it is here.	Ref Inc #216.
224	07:25	65	*S65 Asks a leading question about how to change the position of the paper marker*. So now how do you measure that?	S65 question is of a more general nature.
225	07:26	62	*S62 having looked through the microscope and is confirming with S14 what he is seeing*. So you put it (pointing to the sketch made by S14) on the edge of this and then it moves this way (shows motion by hand).	Note once again that the direction of movement seen through the microscope is opposite to the actual direction of movement.
226	07:35	14	*Ref Inc #223*. As you can see. Why can't you guys understand that, please tell me.	S14 appears to be exasperated with his partners' slow progress.
227	07:50	62	*S62 points out the problem of the conflicting direction of movement*. Then why is it on this side? (Pointing to the sketch made by S14). It should have moved that way (points to the left).	S62 seems confused by the fact that the microscope inverts the direction of movement. The physical movement is to the left but the image has apparently moved to the right.
228	08:00	65	*S65 remains involved and makes a suggestion which is followed*. Why don't we just do it again? Take off the weight.	Ref Inc #225 & 227.
229	08:15	14	See now it has gone back there, look (having removed the weight and looked into the microscope).	S14 has removed the weight he added at 05:50, (ref. #213).

230	08:35	65	*S65 makes a suggestion which is still related to the direction in which the image moves*. Make a mark on it so that we can see which way it moved.	S14 responds by using a pen to make a mark on the paper marker and after this all three students seem reconciled with this observation, although none of them offer an explanation for the image moving in the opposite direction to the movement of the wire.
231	08:40	62	*S62 has been looking at the travelling microscope, and seems no longer concerned with the direction in which the image moved*. We have to subtract the final from the initial.	**EXAMPLE** of how the individual student may work chaotically.
232	08:50	62	*S62 has shifted the attention away from the paper marker to the adjustment of the travelling microscope*. So what you do is you…, just wait, this thing here (touches the position adjustment screw)...	S62 has moved his attention to what has to be done to take the readings.
233	09:00	62	*S62 gives a step-by-step summary of the method to be followed to get the readings*. So you set it up with the cross exactly over there (points to the sketch) and then you take the measurement (reading) exactly, then you put a weight on, and then you re-adjust it , and then you take the reading again .	Ref Inc #225 & #226, in which this discussion was led by S14.
234	09:15	14	*S14 confirms the method explained by S62*. Ok I see what you mean (he looks into the microscope).	The conversation between S14 and S62 appears to have been successful.
235	09:30	65	*S65 has not been part of the discussion and tries to enter the engagement*. Measure what from where? What do you mean?	S65 appears not to grasp the detail of the process just explained by S62.
236	09:50	62	*S62 is explaining the procedure and process to S65*. Here is the wire (makes a sketch on the same pad as was used by S14) and you take the measurement (reading) and then you add the weight and obviously the paper is going to move this way (shows the paper moving to the left).	S65 appears to follow the explanation as he responds "yes", as appropriate.
237	10:00	62	*S62 explains the process of adjusting the travelling microscope*. Then you move that (pointing to the travelling microscope) to exactly that point again and you take the reading again.	This determines what is to be done, but the group still have to work out how to do it.
238	10:40	14	*S14, S62 & S65 have agreed on the process to be followed and are concentrating on the detail of taking the readings*. So now how do we use this? (pointing to the scale on the travelling microscope).	This discussion appears to have a useful dialogue in working out what has to be done to develop a successful procedural strategy.
239	11:15	62	*S62 is working out how to read the vernier scale on the travelling microscope while the other two members of the team are watching him but not participating*. That is 79.5 (After looking at the scale on the travelling microscope for about 30 seconds).	This strategy, of leaving one in the group to become the 'expert' is typical of this engagement. In this case S62 has taken that role (Ref Inc # 246).
240	13:25	62	*S62 announces a reading after looking at the vernier scale on the microscope for some minutes*. It is 79.39.	The group agrees after all three students have looked through the magnifying glass at the vernier scale.

241	13:55	14	*S14 adds a weight to the apparatus, looks through the microscope in order to realign the cross-hairs, and then shifts the whole apparatus. The others shout "No!"* So now I move it back to the same position it was (having just).	S14 seems not to have realised how to adjust the travelling microscope. (Ref Inc #233).
242	14:10	65	*S65 reacting to S14's having moved the whole instrument instead of just adjusting the position of the telescope*. You must not move it (the whole apparatus), you must turn this thing!	S14 tries to work out which adjustments to make while the other two watch him.
243	14:30	62	*S62 tells S14 how to use the adjustment screw*. You must use this (places his hand on the fine adjustment set knob)?	
244	14:30	65	*S65 corrects S62*. No, that is the fine adjustment, this is the coarse adjustment (points to the coarse adjustment knob).	
245	14:50	62	*S62 walks away, rather gumpily, as S14 tries to set up the travelling microscope again*. We are going to have to do this again now.	
246	16:10	62	*S14 has been trying for a minute or so to realign the whole apparatus, unsuccessfully, while the other two are watching him*. What are you doing? (Exasperated, S62 takes over the task of setting up the microscope).	Ref Inc #239, here S62 has taken on the 'expert' role and after briefly relinquishing that role, takes it back.
247	17:35	62	*S62 has set up the microscope and has stood back inviting the others to look at the setting*. Ok (stands back).	S62 standing back as he has is interpreted as his inviting the others to check his work.
248	21:10	62	*S62 and S65 have taken just over 3 minutes to agree on a reading*. (The reading is) 0.13…, don't move the thing (to S14 who is about to add a weight to the apparatus.	It seems that neither of the engaged students know how to read the vernier scale. S14 has played no part in the reading process.
249	21:35	14	*S14 adjusts the position of the microscope after a weight has been added*. Ok (after adjusting the telescope to the new position) You are checking up on me (All three look through the microscope).	S14 has been left to do the sighting and adjustment while S62 & S65 have taken on the role of reading the scale.

From segment #212 to segment #230 in Table 28 the students use the strategy of itemising steps in the procedure and announcing the prediction of an outcome as they resolve the questions of setting up the travelling microscope and approximating the positioning of the cross-wires relative to the edge of the paper marker. Of note is that the problem of the conflicting direction of movement never seems to be resolved explicitly, students appear simply to accept that ‘that is how it is’, without explanation.



2) List all the <u>physics theories and equations</u> you chose to use and give a brief reason why you included each item:

S62

$k_s = \frac{mg}{s}$ (Hooke's law) To find the total interatomic bond stiffness

$N_{chains} = \frac{A_{wire}}{A_{atom}}$ To find how many chains the wire must be divided by.

$N_{bonds\ in\ 1\ chain} = \frac{L}{d}$ To find out how many bonds to multiply by.

$K_{S_i} = (K_S \times N_b)/N_C$ To work at the strength ~~between~~ at interatomic bon between neighbouring iron atoms

3) What were the important <u>features</u> (physical aspects of the apparatus and environment) you included in your answer and give a brief reason why you did so:

Length of wire: This effects the number of bonds per chain.

Gravity: Effects the force applied by the weights on the wire.

ΔL: The abillity of the wire to stretch as force is applied to it.

4) Which <u>features</u> (physical aspects of the apparatus and environment) did you **disregard** and give a brief reason why you did so:

- The mass of wire & weight holder: relatively small compared to the weights.
- Effect of gravity on the horizontal wire: Insignificant
- Uncertainties of Weights: Insignificant
- Stretching of the Adjustment & holder: Over a small distance, should not have a large effect, its also wider than the wire.

Figure 34: Answer sheet showing S62 written response

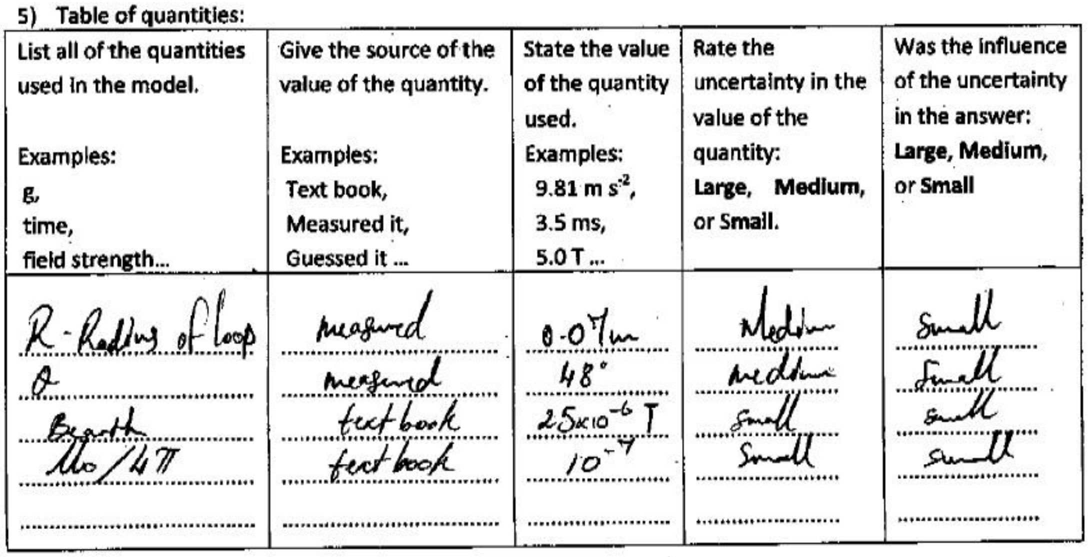
From segment #231 to segment #245 the students deal predominantly with the question of devising a method to perform the necessary measurements and once again the strategy is one of itemising and announcing. It is during the process of devising a method of measurement that whoever is to play the 'expert' role appears to be established. In the presented example there is an anomaly in that in segments #241 to #247, S14 has misunderstood the detail of the preceding discussion about how the microscope should be adjusted. Nevertheless, once the mistake has been corrected and the microscope has been set up by the other two students, S14 once again takes over the 'expert' role of adding the masses and setting the microscope, something he does until the end of the engagement. The problem of reading the vernier was solved by means of the strategy of adopting a 'null' solution in that they never actually worked out how to read the vernier scale, although they did use the strategy of one student announcing the best approximation of the reading and the other checking it.

The answers shown in the example of a student's submission in Figure 34 are typical of the written submissions made and there was no mention made of the difficulties related to using the travelling microscope or reading the vernier scale.

4.2.5.2 Example (2) of strategies of approximation

In the answer sheet, a 'Table of quantities' (question 5) was included in order to prompt students to express a view on how they may have qualitatively evaluated the uncertainty associated with whatever had been quantified. It was expected that this expression may shed light on the strategy that students may use when required to approximate a value.

While there were occasional references in the data to the question of evaluating the uncertainty associated with a measurement, there was not sufficient evidence to show that a specific strategy was employed. Most of the time the students would avoid the evaluation of the uncertainty associated with measurement entirely. The view expressed by student S14 in an interview is considered typical of the responses to the requirement to fill in the rating of the uncertainty in the value of the quantity used. During the interview the written submission shown in Figure 35 was discussed:



S14

5) Table of quantities:

List all of the quantities used in the model. Examples: g, time, field strength…	Give the source of the value of the quantity. Examples: Text book, Measured it, Guessed it …	State the value of the quantity used. Examples: $9.81\ m\ s^{-2}$, 3.5 ms, 5.0 T …	Rate the uncertainty in the value of the quantity: **Large, Medium,** or **Small.**	Was the influence of the uncertainty in the answer: **Large, Medium,** or **Small**
R - Radius of loop	measured	0.07m	Medium	Small
θ	measured	48°	medium	Small
B_{earth}	text book	25×10^{-6} T	Small	Small
$\mu_0/4\pi$	text book	10^{-7}	Small	Small

Figure 35: Written submission by S14 showing assessment of uncertainty

36:48 I: Can you recall how you approached the requirement to fill in the (quantities) table?

36:52 S14: Honestly, we didn’t give it that much thought.

36:55 S14: [Reads the written submission] Maybe if we approximated something then it would have been medium.

37:13 I: Did you have some difficulty working out what that meant, how you had to respond to the question?

37:16 S14: Not really, we just thought like…, this whole page [shows page 2 of the answer sheet] was basically um…, subjective and you could use your own opinions. We didn’t think that…, we would be marked strictly on this page.

37:53 S14: Up to here [places his hand like a barrier just above the table on the answer sheet] we just stopped thinking. [laughs]

38:02 I: Something that was noted in your submissions was that in every case except one, in all seven minilabs, whenever it was something that *you* measured, you wrote that the uncertainty was medium.

38:15 S14: Ja, well, when you measure something there is always uncertainty.

38:20 I: You didn’t think that if you measured it you would be certain to get it right?

38:25 S14: No! We did that whole uncertainty thing in the yellow book (referring to *Introduction to Measurement in the Physics Laboratory: A Probabilistic Approach*, Buffler, Allie, Lubben and Campbell, UCT, 2010, the manual on uncertainty analysis used in the laboratory course). What can you be certain about? [laughs]

38:40 I: But here for instance [points to the written table] it looks as if, when it comes out of the textbook, then it looks like the uncertainty is small, and if *you* measured it, it looks as if the uncertainty was medium.

38:48 S14: Ja, that is my experience of that yellow book.

39:00 I: Try to explain that a little more for me, what do you mean?

39:10 S14: What I got from the yellow book is that it teaches you how to do experiments, factors you need to consider…, and from there you apply the theory from the textbook and the practical experience from the yellow book onto this problem that they set us. You are using all these experiences and it is all coming together here.

39:30 I: If I interpret you correctly, the yellow book said to you that you cannot be sure about anything?

39:40 S14: Ja…, I did say that, I am sure I said that in my paragraph…

39:45 I: So, if *you* measured something, then you seem to say that the uncertainty is medium, but maybe if someone else measured it, then the uncertainty is small?

39:50 S14: Ja, medium…, because if you say large…, it’s a bit [gestures as though it is unreasonable], I don’t want to get marked down for that…, ja…, medium is safer.

40:00 I: So medium is safer from a marks point of view?

40:04 S14: Ja.

As noted above, while students expressed an awareness that they should take readings as accurately as possible, and that they could use techniques like setting the scale of an instrument to read from zero[10] or taking multiple readings, these strategies were seldom used.

4.3 Findings regarding the coupling of strategies

Having considered, in the previous section, a ‘thin’ description of the strategies adopted by physics students when modelling solutions to hands-on tasks, the next step is to consider a ‘thick’ description of the same findings. However, in order to do so, it is necessary to take cognisance of the findings with regard to the coupling of strategies that was observed in the analysis of the collected data.

In 3.7.4.1 above, a description was given as to how a pictorial representation of the student groups’ engagement with the minilabs was derived. From the way in which the action phrases and the strategies were linked together, it was observed that there was a coupling of strategies, i.e., there appears to be a coupling of: 1) the strategies of *itemising* and *announcing,* and 2) the strategies of *doing* and *checking*. The exposition of this coupling of strategies is presented below.

4.3.1 Findings regarding the strategy of coupling itemising & announcing

Throughout the student engagement with the minilabs it was observed that there is a pattern, of a propositional nature, that goes on in the general discussion between the members of the group. This discussion is characterised in these findings as an interplay between *itemising* and *announcing* (these are terms coined by the researcher and are defined as follows):

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[10] It is not known if the students set the scale to ‘zero’ to make the reading and calculation easier or whether they interpreted this to imply that there is a reduced uncertainty associated with setting the instrument to ‘zero’.

1) *Itemising* describes the student making a proactive, suggestive proposal, e.g., “we should do this, then that…, etc.” The strategies employed in itemising have been coded as strategies of itemising: a) variables in a formula, b) steps in a procedure, and c) physics concepts.
2) *Announcing* describes the student saying something passively, in a matter-of-fact way, e.g., “if we do this, then that will happen…” The strategies employed in announcing have been coded as strategies of announcing: a) the prediction of the outcome of an action, b) a value or a reading taken, c) the result of a calculation, d) an observation, and e) (asking) “What’s going on?” or “What is this?”

The use of the coupled itemising and announcing strategies do not appear to be confined to any particular modelling process as they are ubiquitous in the students’ general discussion. From Table 31, which shows the frequency and the % use of the strategies, it can be seen that approximately 40% (codes 31 to 45) of the total number of coded segments are associated with the strategies of itemising and announcing.

4.3.2 Findings regarding the strategy of coupling doing & checking

Distinguishable from the general strategy of itemising and announcing, it has been found that there is another pair of coupled strategies, that of *doing* and *checking*. This interaction is characterised by a student doing something and then stating a proposition in which there is the implied question, “… is that correct?” The other members of the group will respond accordingly.

The coupled actions of: 1) selecting & verifying, 2) measuring & confirming, and 3) calculating & verifying were observed to be so coupled in the engagement of all of the groups and the use of strategy coupling in this way is illustrated in Figure 36.

However, unlike the general interaction strategies of itemising and announcing, the coupling strategies of doing and checking can be associated with one or more of the modelling processes as follows:

1) the checking (verification) of a selected formula, example or physics principle is associated with *particularisation* and *application*.

2) the checking (confirming) of a measurement is associated with *idealisation* and *approximation*, and
3) the checking (verification) of a calculation is associated with the *realisation*.

From Table 31, which shows the frequency and the % use of the strategies, it can be seen that approximately 20% (codes 21 to 23 and codes 51 to 63) of the total number of coded segments are associated with the strategies of doing and checking.

4.4 Strategies adopted with respect to cyclic problem solving in minilabs

To gain further insight into the way in which strategies are employed in the modelling processes, it is useful to consider the strategies in the light of the sequences of action and interaction that were observed as the students applied those strategies.

As has been noted in 3.7.4.1, an analysis of the student interaction shows a pattern by which the student groups engage with the apparatus by coupling strategies. Further analysis revealed that there is a pattern of engagement that has a cyclic nature. In order to explore the adoption of strategies in the context of the observed cyclic engagement by the group, it is necessary first to describe the stages and the key characteristics of this cyclic pattern.

4.4.1 The 3-stage evolution of the student engagement

In this section the findings are presented regarding the evolution of the engagement through the observed stages of:

1) *exploration*,
2) *formulation*, and
3) *conclusion*;

as well as the cyclic nature of the engagement in the formulation and concluding stages. This three-stage evolution is loosely based on the general model development proposed by Hestenes (1987), and which has been presented in Figure 2.

When considering the possible evolution of the strategies students may employ while engaged with the minilabs it is evident that, generally, students do not start out with some clearly defined strategy in mind. Even when students had reported during the interview that they had done some preparation beforehand and “had a fair idea as to what to do” (segment #179 and segment #198), the observations suggest that it is very seldom that students have a pre-planned sense of what to do. Typically, students start with the actions of exploring and familiarising, (see Table 10), effectively employing the default strategy of asking “what’s going on?”, “what must we do?” or “what is this?” During this exploration stage the students evaluate the group responses as they work out what to do.

The transition from the exploration to the formulation stages comes about when the group has particularised (selected) a formula that is to become the focus of their engagement. Significantly, in every one of the 31 observations made (see Table 2), this was the galvanising point that signalled the end of the exploration stage and the beginning of the formulation stage. Moreover, it was observed that the groups’ particularisation of a key formula appears to set off the evolution and employment of all the other strategies.

The formulation stage is the stage in which the group formulates the physical model. It is the stage in which the use of coupled strategies is abundantly evident as students ‘itemise’ and ‘announce’ in their deliberations, and ‘do’ and ‘check’, as the group particularises, applies, idealises and approximates to formulate the physical model. It is relevant that the use of the word *group* in this context is deliberate. The engagement pattern observed and described in this section of the findings refers to the progression of the modelled solution by the group; noting also that the progression of any one individual may show a trajectory that is much more chaotic.

The transition from the formulation to the conclusion stage comes about when the physical model is substantially complete and the group appears to have satisfied itself that enough information to answer the posed question has been reached. At this point the group disengages from the apparatus and the focus moves to the calculation and checking of the answer to the minilab question.

The conclusion stage is a stage during which time the physical model is converted into the conceptual model.

From the observations made in the present work, it was seen that while the exploration stage appears to be quite unpredictable, the group's engagement during the stages of formulation and concluding proceeds in a cyclic pattern as shown in Figure 36 appeared to be followed consistently by the group.

4.4.2 The cyclic nature of the student group engagement

To facilitate the discussion of the findings of the cyclic nature of the students' group engagement with the minilabs, the figure presented in Figure 26 is reproduced in Figure 36.

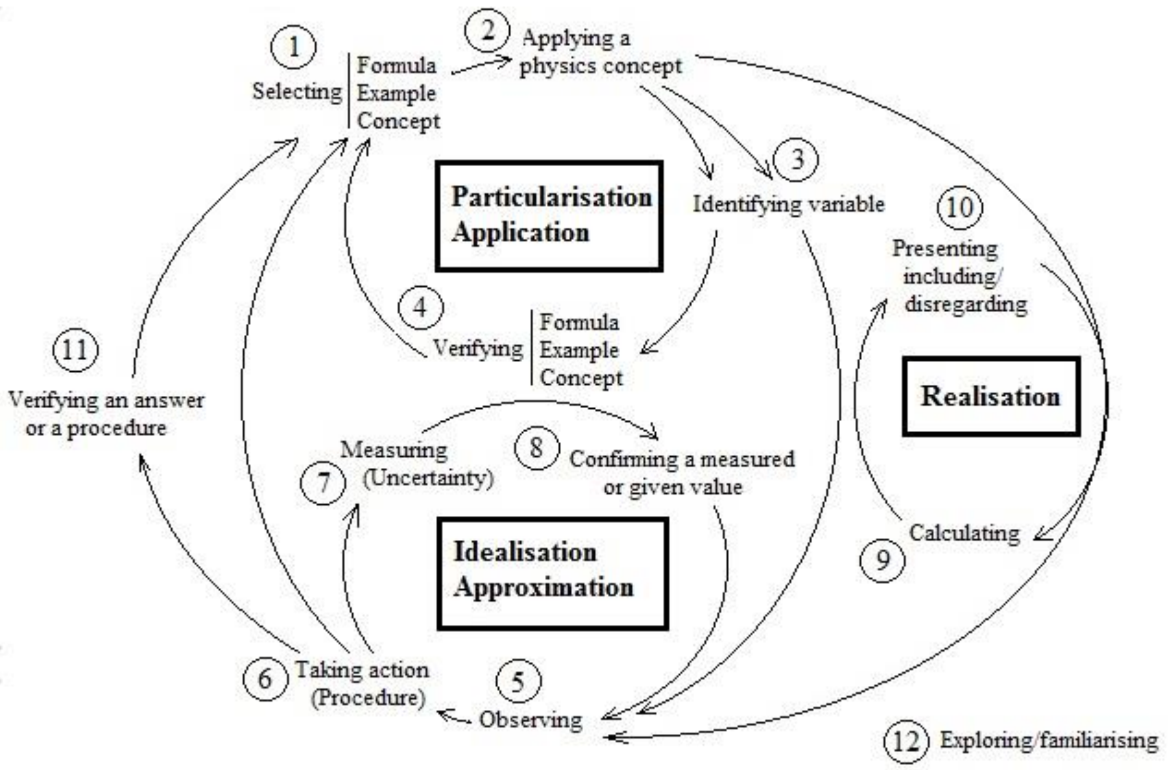

Figure 36: Proposed cyclic pattern in student group's engagement with minilabs

In the observed cyclic pattern there are five discernible action cycles (loops) and all but one of the actions listed in Table 10 are situated on one or more of these action cycles. The exception is the exploring/familiarising action that showed no consistent relationship to the other actions. In the interpretation of the cyclic pattern it is important to note that while the action phrases are linked to one another by means of an arrow, which implies a direction in the process, this convention is not adhered to in any strict sense. It may well happen that when required, the group will oscillate between two actions before moving to the next action in the cycle.

A useful way of interpreting the application of the cyclic pattern diagram is to think of it in terms of what may be described as the 'rules of engagement.' By this analogy, the action circles may be seen as circular tracks along which the *group* may cycle until they have reached a concluding stage where the group believes it has enough and appropriate information to answer the posed minilab question. Once again the point is made that this description refers to the *group*, and does not necessarily describe the behaviour of any individual. In this regard elements of complexity theory, namely that the group dynamic is structured and predictable while the individual engagement may be chaotic, appears to be relevant (Baranger, 2000; Mitchell, 2009). Also of relevance is the idea that model-based reasoning occurs in a 'distributed cognitive system' and that "the reasoning processes take place not just in the mind of a (single student), but across (students) and artefacts within the problem space of the laboratory" (Nersessian, 2006, p. 708).

For the group, the rules of engagement are that: 1) the group does not need to do anything when an action point comes up as they cycle through the process, they can just pass the point and return to that action later on, and 2) the group can cycle through the action pattern as often as they feel they need in order to gather information or experience about the posed problem.

However, for the individual student, the rules of engagement are quite different and are described as follows: 1) the individual student can start (engage) or stop (disengage) at any time, 2) the individual student can be anywhere in the action pattern at any time, i.e., the individual may not be working on whatever the group is doing, 3) depending on where the individual student is in the action pattern, he/she can draw the group's attention to anything at any time, and 4) any individual can express confusion or disagreement whenever he/she likes. Of note is that when an individual expresses confusion or disagreement, the group may or may not react, depending on what the group engagement (distributed cognitive system) is working on at the time.

4.4.3 Strategies with regard to the *exploration* stage of the cyclic pattern

In the present work, the observed action of exploring/familiarising has been identified as representing the ‘exploration stage’ of the engagement and it was noted that typically this stage would last for some 3 to 6 minutes, although there were unusual cases in which this stage lasted for more than 10 minutes. As has been noted, the exploration stage ends when the galvanising point was reached in which the *group* had selected a formula that was to become the focus of the engagement.

The exploration stage is characterised by the students making observations and identifying variables as they employ the strategies of itemising and announcing. These coupled strategies are employed fairly randomly at first and there is no discernible pattern in the way in which they are applied initially, for as has been noted, groups of students do not appear to set out with an explicit plan in mind. It is during this stage that the students who may take on the role of the ‘expert’ are most likely to emerge. The actions of selection and observation, as students familiarise themselves with the minilab problem and the apparatus, correspond to those used in the strategies employed in the processes of particularisation and idealisation (see Table 18 and Table 24).

4.4.4 Strategies with regard to the *formulation* stage of the cyclic pattern

The formulation stage is characterised by all four of the processes, *viz.*, particularisation, application, idealisation and approximation, required to form the physical model.

The group will go through the particularisation/application cycle of checking the variables by applying the strategies of itemising and announcing, e.g., “We have this. Do we need that? What about this?”, and once the particularised formula has been verified the group will proceed to the idealisation/approximation cycle where they will employ itemising and announcing strategies as they take the readings and go through the checks of the measurements made. During this stage those students who have taken on the mantle of the ‘expert’ will generally play the role they took on in the exploration stage.

Throughout the formulation stage, individual students will continue to raise different questions about what they believe is to be done and almost always the reason for doing so is because the students are keen to “get it right”. At this stage the strategy of ignoring some observed phenomena is also in evidence as the group may or not accept as relevant a comment or an observation made by an individual. In the event that the group accepts a suggestion that they have to make a correction or that they have to make a change in what has been particularised, the group will move back to the particularisation/application cycle and they will go through the process again.

4.4.5 Strategies with regard to the *conclusion* stage of the cyclic pattern

There comes a time in the engagement when the group appears to agree that they have enough information to answer the posed minilab question and when this happens the students enter the concluding stage. As has been noted, the onset of this stage is when the group focus moves from the apparatus to calculation and confirming the answer to the minilab question. It is inferred that at this point of the engagement the group would have developed a physical model adequate to solve the posed minilab answer, i.e., a physical model adequate to present a coherent conceptual model, and at the same time the majority of the individual students would have developed mental models commensurate with that physical model. In the event that the group concludes that they have not solved the problem they may cycle back to the formulation stage.

This concluding stage is characterised by the actions of calculating and presenting (their written submissions) as the students employ the coupled strategies of doing and checking. The actions and strategies employed in this stage correspond to those used in the process of realisation (see Table 23). During this stage students employ the strategies of using multiple representations and checking on the feasibility of a calculated value. In those cases where students are to employ the strategy of using data selectively, i.e., by ignoring some data taken and/or possibly ‘making up’ data, then it will be used at this stage.

This conclusion stage may be considered to be the equivalent of the ramification and validation stage proposed by Hestenes (1987), presented in 2.4.1 above, where the special properties and implications of the model are worked out in the largely mathematical ramification stage, and where the validation "is concerned with empirical evaluation of the ramified model" (p. 446).

4.5 Findings regarding the strategy of using the 'expert' role

When observing the student group dynamics as the minilab tasks were undertaken, it was noted that the strategy of letting a particular student take on the 'expert' role was widely adopted. By the 'expert' role it is meant that a particular student has taken 'ownership' of a some specific action such as reading a scale, setting an instrument, placing masses on a balance, writing down readings or starting a clock; and that the other students have accepted that person as the one who is to perform the 'expert' role.

From the observations in this study it was generally possible to identify an individual who appeared to take role of the group leader, but what was also observed was that the person who took on the mantle of the 'expert' was not necessarily the group leader. There is evidence in the data to show that any student may take on an 'expert' role, as long as they are accepted as such by the other members of the group; and once having been accepted as the 'expert', that student may become quite possessive of the role as can be seen in the following example:

At segment 314, minilab #3, case #1, location #06:00, student S63 is adjusting one of the wire markers to align with the bottom of the mass that is to oscillate while the others are looking on and when they make suggestions as to how he should do the job he responds, "You know what, I am in charge of taking this measurement." For the rest of the engagement the other students accept S63's readings of this aspect of the work, without exception.

Taking on the 'expert' role does not necessarily mean that the student who has done so has always "got it right." Indeed, in minilab #2, case 2, (segment 742 to 781), a student, S74, is designated as the 'expert' to read the vernier scale on the travelling microscope, but it is clear from the video observation, and the readings taken down, that he did not actually know how to read the vernier `scale; a fact that was confirmed in a discussion with the student two weeks later. Nevertheless, the other two students in the group were none the wiser, even though one of them, S33 actually checked the readings announced by S74.

It is suggested that an important reason for allowing a student (who appears to be competent in the role) to take on the 'expert' role may be expediency. It appears as if this strategy allows them to get the job done sooner even though it may stifle the engagement of other students.

4.6 Findings regarding the students' views of the 'modelling' concept

Strictly speaking, the students' views of 'modelling' does not fall within the ambit of the research questions of this study, but since the research questions were framed within a model-based view of physics, a specific question about modelling was included in the interview to provide supplementary information. The question was:

> "In the PHY1004W course you have been told about modelling, what do you think modelling is all about?"

From the selection of students' responses shown in Table 29 it can be seen that the processes of particularisation, application, realisation, idealisation and approximation are recognised at various times by different students (not using those words however), but, as noted by student S42, there does not appear to be any conscious sense of 'modelling' on the part of the students. Apart from the occasional reference to these responses, no rigorous analysis of this aspect of the data was done.

Table 29: A selection of student views on 'modelling'

location #	Student S#	**Interview transcript of students' response to the question, "what is modelling all about?"**
39:40	4	I think a model is a simple understanding of (the phenomenon)… definitely idealised, it is not reality at all. So… I wouldn't know what to use as an example, but (Modelling is doing) small scale experiments to understand bigger theories. A lot of things on a smaller scale going upwards trying to understand how things kind of react.
03:07(B)	7	It is a way of recreating something so that you can mimic what you expect to happen... a model can seem accurate but it does not necessarily mean this (a prediction from the model) is going to happen. We can verify what is going to happen in the model and it might apply… (to reality).
43:20	8	It is sort of manipulating something in such a way that you understand how it works… you try to make it (the model) as similar as you can to the real world.
32:24	13	Even though sometimes I do not think of it as getting (deriving) a model, I know I have to get a picture of… say I am doing an experiment, then I have to get a whole picture of it (the experiment) and for that I have to get a model so that I can carry on.
43:36	16	It is sort of just taking the things that you know and then trying to test (what you know) by coming up with… what all this is… trying to apply the physics.
46:08	20	Trying to make a simple understanding of something that is a bit more complicated… explaining something in simple physics terms.
48:35	24	(Modelling) is science really, at its barest bones. I think modelling is very difficult… modelling is the goal in the end… I would think of the Biot-Savart law as a model… basically, everything (in science) is a model.
35:00	36	I have heard the word 'modelling' a lot (in the physics course). Ok, let's see… say you are given a certain problem and you have to make certain assumptions, because no problem can be solved exactly... so a model is something that is made from certain assumptions.
34:05	42	It is trying to explain complex phenomena in a simple way… I don't think I have ever really thought of (engaging in minilabs) as, '*I am modelling a situation*,' … ja… you come up with a model to try and explain what is going on.
37:29	45	I don't think minilabs helped me to think about how to model things… but at least it helps me to make assumptions that I have to make about things… and what I have to take into consideration.
44:56	63	I think it is about identifying the general trend of what people do and how they go about doing it… it is a way to understand why people do certain things.
12:14(B)	70	Well, taking real life systems and the way things are, and trying to represent them in a way that allows you to make predictions… more or less. And with that comes simplifying assumptions
38:45	74	Modelling is basically taking a system and stripping out all the complications… and putting everything in simple form and then using that elementary form to observe and to compare it to what we see in real life.

5 Discussion

5.1 Recognising strategies

This discussion takes the notion that the employment of a strategy is a metacognitive process which refers to “conscious and deliberate thoughts that have other thoughts as their object” (Hacker, 1998, p. 8), as a point of departure. Furthermore, in considering the strategies used, this discussion embraces the views on the selection of problem-solving strategies as proposed by Goodson (2000) and Moseley *et al*. (2005). It is also accepted that the adopted strategies cannot be observed directly, but are inferred from the observed actions in which the students engage, and that the reasons for the selection of these strategies are thus also inferred from the observed engagement.

5.2 The delineated approach to discussing student strategies

While this study is presented in a delineated fashion by discussing particularisation and application, idealisation and approximation, and realisation as separate processes, there is, within the data, evidence to suggest that when students engage with the minilabs, different strategies involving one or more of the defined modelling processes are often employed simultaneously, and in different combinations. Moreover, there is little or no evidence in the data to suggest that students are conscious of any such delineation as they adopt the various strategies.

5.3 Strategies adopted within the study’s model-based view of physics

5.3.1 Strategies in the formulation of a physical model

It has been suggested by Buffler *et al*. (2008) that there are particular pedagogical advantages in the view that the process of physics problem-solving occurs at the level of the physical model. Therefore the strategies adopted, as shown in the findings of this study, are considered in the light that they may shed on the formulation of physical models; and ultimately, on the formulation of the conceptual models that represent those physical models. To this end, it is useful to recall the view of Greca and Moreira (2001) when they considered the relationship among mental, physical and mathematical models. In their view, 'modelling' was understood "*as a facilitating process for the construction of adequate mental models that will help understand physical models* (italics in the original)" and that "the learning of the semantics of theories should precede the learning of its syntax, that is, the mathematization (*sic*) should be a later step and not a central one" (Greca & Moreira, 2001, p. 119).

While neither of the questions: a) What is the precise nature of students' mental models? nor b) What is the precise nature of the various possible corresponding physical models?, were objects of research in the present work, it is suggested that the strategies adopted in the implementation of each of the defined modelling processes will have a bearing on the mental models and the corresponding physical models so constructed. And so it is suggested that from the findings of the present work, it is possible to infer something of the nature of the physical model *vis–à–vis* its semantic and/or syntactic nature. Having noted that the students' physical model, which gave rise to the presented conceptual model, can only be inferred, it is recognised that this inference is limited to the researcher having to compare the communicated student's conceptual model with their personal physical and/or conceptual model. And even then, the comparison does not consider whether the student and researcher's conceptual models are the same, but merely whether they are commensurable.

From the findings it can be seen that for at least 80% of the students, the strategy of selecting a formula was central to the processes of both particularisation as well as idealisation; and it is suggested that this selection sets the pattern for the whole minilab engagement. Indeed, the findings suggest that undergraduate physics students who engage in hands-on tasks of this nature do so within a predominantly formula-centred problem-solving paradigm (Van Heuvelen, 1991). The reasons as to why the significant majority of students operate in such a strongly formula-centred paradigm was not specifically researched, save to say that from the reasons for adopting whichever strategies were adopted, it is evident that the students wanted to employ methods that were procedurally correct, and that the chosen formula played a key role in the selection of strategies that it was believed would produce the correct answer.

When considering the paradigm within which students engage with hands-on tasks, it may be useful to consider the following views on epistemologies and modelling processes. It has been suggested that in order to make contributions to the worldview of science, the physicist has to have what would be described as a sophisticated science epistemology. To quote Smith and Wenk:

> More specifically, if one's epistemological understandings in a given field function as a kind of metacognitive control structure, then they would guide one's goals, reasoning and sense making in situations in which they are activated. For example, they could guide how one structures first-hand inquiry, reasons about scientific controversies, conducts searches for reliable information on science topics, approaches learning difficult science content, and designs classroom inquiry experiences (Smith & Wenk, 2006, p. 748).

And as suggested by Greca and Moreira,

> the process of modelling involves the perception of a system, a phenomenon, or of problems to which one can apply a particular physical model, which already exists, and for this reason it is a process with a high "semantic" content. The learning of modelling practices by scientists seems to be made by a cognitive enculturation similar to the way a person learns his/her language. The kind of knowledge acquisition, which is tacit, is costly in terms of the time necessary to attain it and, in fact, it would seem that it is only learned by the students along their way to become physicists, and by the physicists themselves (Greca & Moreira, 2001, p. 119).

From the observed student group discourse and engagement with the hands-on tasks, it is suggested that student modelling is indeed governed by their epistemology and modelling skill, rather than their ability to manipulate physics formulae and to apply measured values to those formulae. The students generally had no difficulty taking readings and realising a conceptual model that was adequate to answer the posed question. However, as was also noted in the findings by Greca and Moreira (2001), it seems that students often work solely with formulae and definitions because they are not able to construct appropriate mental models of the physical models for the theories. For the most part, it seems that the students do not address the 'semantic' aspects of the posed problem but select their strategies from a 'syntactic' view.

This syntactic approach is well illustrated in the strategies adopted by students when engaging in minilab #5, a task in which a charged ruler is used to lift a piece of paper. In modelling the solution to this minilab, the solution called for the semantic formulation of a relatively complex physical model from a range of physical theories and a multi-faceted real world phenomenon. Indeed, there was no single formula that could be applied and there was no single variable to measure, so many students did not even go to the laboratory to make any observations as they considered they "had seen it already" in a lecture demonstration. Moreover, despite the consistent sketching of electric field lines by the lecturers in lectures when charge distributions in space were discussed, only two students made sketches of the expected electrical field lines between the ruler and the table; suggesting that there was little engagement with the semantic aspects of the theory. During the interviews there were exceptions where students would indicate that they had discussed whether, for example, to consider the paper as a conductor or an insulator, but generally the interviewee did not recount an episode to suggest that they had considered the semantic aspects of the physical model as opposed to merely attempting to choose a mathematical formulation.

In considering why students may not engage with the semantics of the model, it may be useful to return to the question of student epistemologies. The terms 'level' and 'stratification' by Smith and Wenk (2006) in regard to student epistemology suggests that there may be an identifiable epistemological topology whereby students will initially engage with the process with the intention of amassing a collection of 'true beliefs' and from there they may begin to link explanation and hypothesis, finally giving them the wherewithal to be able to revise existing theories for themselves. The submission here is that there is a path of progress in a student's development from a 'simple facts' epistemology to a sophisticated understanding of the nature of science. And so, in order for students to make sense of the tasks with which they have been presented in a teaching and learning environment, the given problems have to be pitched at a level commensurate with the "productivity of (their) epistemological beliefs" (Elby & Hammer, 2001, p. 555) which in turn, reflects their productive epistemological resources.

And as noted previously, Hammer and Elby have suggested that students "almost certainly have (epistemological) resources for understanding *rule systems*, such as sports and games." They have "abundant informal experience working with representations and representational systems" and "students' skill at construction suggests that they also have (epistemological) resources for understanding the actions of checking, repairing and refining" (Hammer & Elby, 2003, p. 60-61). Indeed, the findings by Hammer and Elby are reflected in the findings in the present work in that students consistently use strategies that resemble *rule systems*, i.e., they follow the action patterns in which they make extensive use of strategies for 'checking, repairing and refining' when engaged in particularisation and application as well as in idealisation and approximation.

Finally, it has been shown in studies to do with theoretical physics problem-solving, that strategies often employed by college students involve working: "a) by trial and error, b) 'backwards' from a numerical answer provided in a textbook, or c) by invoking a solution presented in class to a problem that they wrongly assume to be similar to the one on which they are working" (Halloun, 1996, p. 1019). In the observations of students engaged with the minilabs, as well as in the written work, there is evidence to suggest that in modelling a solution to the minilab task, some students may well be working 'backwards' towards an answer that may have been given to them by others, possibly by a fellow student. If this is so, then it would further support the possibility that at the time of the engagement with the minilab the students were not occupied with the formulation of a physical model appropriate to the hands-on task, but that their approach was much more in line with what they do when engaged in tutorials and problem sets, a topic to be discussed in 5.4.2 below.

5.3.2 Strategies in idealisation and approximation in a broader context

While this part of the discussion relates to the research question to do with the strategies adopted when required to idealise and approximate real world phenomena, it considers the findings in the broader context within which students are required to apply these strategies.

The intention in the stated objectives of the *Matter & Interactions* curriculum regarding the role of laboratories is clear: it is to allow, *inter alia*, for an environment in which students "spend most of their time working on hands-on observations, 'tangibles'" (Beichner, Chabay & Sherwood, 2010, p. 456), and "in this process students need to make approximations, to idealise complex systems, and to think through the consequences of a particular model – activities that are central to physics but are absent from the traditional curriculum" (Chabay & Sherwood, 1999, p. 1045).

With due consideration for the inherent difficulties associated with modelling, Chabay and Sherwood (2011) have given, throughout the *Matter & Interactions* text, notes and explanations on questions of modelling. For example, on p. 82 in the 3rd edition of *Matter & Interactions* there is a discussion on physical models and idealisation; on p. 369 there is a discussion on a model for dry friction; and on p. 866 there is a case study on sparks in the air, for which three models are developed and discussed at length. These aspects have been given this attention because it has been widely recognised that "the ability to make connections between the formalism of physics and real world phenomena needs to be expressly developed" (McDermott, 1991, p. 306). As illustrated in an article by Mermin (2009), "the distinction between real and abstract is notoriously problematic", which, that author suggests, has resulted in many physicists developing a habit whereby they, "wrongly confer reality on something abstract (and) inappropriately reifying successful abstractions". Mermin uses the example of when he was an undergraduate learning classical electromagnetism, he was enchanted by the idea that electromagnetic fields were real; it was only later that he came to see them as "clever calculational devices" (Mermin, 2009, p. 8-9). This illustration suggests that the successful physicist needs to mature to the stage where he or she is able to idealise and approximate real world phenomena so that the outcome of these processes can be incorporated into a completed physical model. In this regard it is worth repeating the point "that understanding the theory/experiment relation is a key meta-scientific ingredient in enhancing the ability to think scientifically" (Portides, 2007, p. 700).

But how does the student of physics develop an understanding of the theory/experiment relation? Consider, for example, an explanation given by Richard Feynman in his book *Six Not-So-Easy Pieces* (1997) where he discusses vectors, symmetry and translations. In the introduction to the topic, Feynman has proposed a hypothetical case in which a machine is observed to work in a certain way in one location, and then the machine is moved to some other location where the functioning of the same machine is observed once again and the outcomes of the operation at each of the two locations are compared. Feynman uses this analogy to explain the concept of inertial frames and goes on to show how some physics properties are invariant in translation from one frame to another, while other properties are not. Central to the understanding of this conceptual model is the question as to which parts of the inertial frame should be moved and which to keep common? Feynman explains, “It is clear that what we want to do is to move all the essential influences, but not everything in the world. *ibid.* … it turns out in practice that with a certain amount of intelligence about what to move, the machine will work,” and here Feynman is rather glib stating simply, “All of our ideas in physics require a certain amount of common sense in their application; they are not purely mathematical or abstract ideas” (Feynman, 1997, p. 2). However, it is suggested that knowing which influences are essential and which influences can be ignored when devising a physical model probably requires more than just a certain amount of common sense.

There is a further significant factor to be taken into account when considering the students’ response to the requirement to idealise and approximate the real world phenomenon presented to them in the minilab, and it is the question of theory-laden observation. To illustrate this point, an example is given from the findings and interpretation of the present work by considering the task in minilab #4 in which the students have to determine which properties of the rotating wheel (the real world phenomena) they are to include in the physical model. When students have to determine the descriptors of the wheel so that they can be quantified for inclusion in their model, they appear not to actually go through the process of transforming the wheel in front of them[11]. At segments ref. #426-429, ref. #472 and ref. #482 of the Master look-up table, it can be seen that students declare the wheel to be friction-free before they have made any real observation of the actual rotation of the wheel and in doing so, they appear to include in the physical model the properties of an associated wheel. Certainly the dimensions, such as the diameter of the wheel, as used in the

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[11] As explained by Mermin (2009), in the reifying of predictions made through the operation of some previously devised physical model, it is not uncommon to find that physicists do not make the clear distinction between the reified event and the real phenomenon. It is just such a lack of distinction that leaves students of physics overlooking “the fact that quantum states are merely useful abstractions.” Mermin illustrates this view by saying that a person is not a “continuous field of operators on an infinite-dimensional Hilbert space” (Mermin, 2009, p. 8), a point first made by Einstein who suggested that, “space and time are modes by which we think, not conditions under which we live.”

physical model may come from measuring the actual wheel in the laboratory, but other relevant properties of the wheel could well be those of an associated, already idealised wheel as seen in the textbook.

In this way it would appear that theory-laden observation (Hanson, 1958; Brewer & Lambert, 2001), automatically excludes some properties that may be relevant to the physical model - objects like the table-top, because the surface of the workbench is never part of the idealised problems of the sort that are presented in the textbooks or in class.

The question of the exclusion of the table-top is illustrated in the findings of the present work by the observation of students' modelling of the attraction of charged paper in minilab #5. As noted earlier, of the seven minilab tasks, this was the easiest to do, because there was nothing to measure, but it was the most complicated to model because of the complexity of the physical model that could be formulated. It has been reported that some students presented an answer to the modelling problem without actually going to the laboratory at all as they appeared to base their idealisation and approximation on what they had seen in class. Of those students who did go to the laboratory to observe this phenomenon, and who were subsequently interviewed, the question was asked, "Show me, by using your hand, how the paper reacted to the charged ruler (that was suspended over it)?" Every one of the students gave an accurate description of how the paper first 'stood up', seemed to be 'attached' to the table, and then jumped up to the ruler. So, while every one of the students who went to the laboratory, and who were asked about it, had seen that there was an attraction between the table and the piece of paper, none of them mentioned this anywhere in their submissions. When asked about the possible reason for the paper being attracted to the table, the majority of students were able to give a coherent physics explanation for the observed phenomenon in terms of the polarisability of materials and charging by induction, but when asked why they ignored a relevant observation that they had clearly made, none was able to give any explanation for this omission. It is suggested that the reason why they ignored this observation was because the table-top was not part of their theory-laden perception as it is never shown in associated examples in the textbook or tutorials or problem sets.

With due cognisance of the complexities of idealisation and approximation, it may be suggested that few students who were part of this study went through the process of consciously idealising the real world situation in front of them. They selected what had to be ‘idealised’ from the itemised variables in the chosen formula; and any other phenomena that may have observed, except for those features itemised in the particularised formula, were ignored. It is speculated that if there was little conscious idealisation (as defined in the model-based view of the present work), then there may well have been little “semantic” development of a requisite physical model from the real world perspective.

Where students were required to quantify variables, they generally had no problem obtaining appropriate readings using the instruments at hand, even to the extent that they would take steps to reduce the uncertainty in the measurements. The implication of this being that they were approximating variables to what may be thought of as being a correct estimate of the quantity in question. Of significance is the role of the ‘expert’ in the process of drawing information into the physical model: students will readily defer to one of their number who appears to display competence in the processes of approximation, even if the ‘expert’ is doing the incorrect thing.

5.4 Strategies in model-based reasoning and distributed cognition

In considering the strategies that students adopt at both the level of the specific research questions as posed in 2.1.7, as well as in the broader context of ‘modelling’, it is relevant to point out that for the purpose of this discussion, it is a key assumption that there is a form of reasoning that can be described as ‘model-based reasoning’. Furthermore, in the context of minilab engagement by groups of students, that model-based reasoning occurs in a distributed cognitive system involving co-constructing and manipulating physical and mental models. These reasoning processes take place not just in the mind of a single student, but across the group of students who are engaged with the minilab (Nersessian, 2006). Moreover, it is assumed that a) this reasoning, as with the reasoning by individuals as suggested by Johnson-Laird (1983), is of a propositional nature; and b) that “model-based reasoning is closely bound up with analogy” (Nersissian, 2008, p. 184), as in the analogies described by Clement (2009). Finally it has to be recognised that the group has what Hammer and Elby (2003) referred to as ‘epistemological resources'; resources that are brought to bear in developing the solution to the hands-on tasks.

5.4.1 Strategies used within a cyclic pattern

As has been noted in the section of the literature review in which the sequencing of modelling processes was researched by others, it was noted that the cyclic nature of the student engagement had long been recognised (Justi & Gilbert, 2002; Halloun, 2007; Etkina & Van Heuvelen, 2007; Zwickl, *et al.*, 2013)[12]. Furthermore, based loosely on a strategy for model development proposed by Hestenes (1987) and shown in Figure 2, it is suggested that student engagement with the minilabs may be considered to have taken place in a three-stage process where the stages of *exploration* and *formulation* have to do with the development of the physical model, while the *concluding* stage has to do mainly with the realisation of the physical model as a conceptual model. Once again, the delineation of the employment of these strategies is for purposes of clarity; the strategy implementation is not delineated as presented here. And it should also be noted that while the stages of model development suggest a chronological order, that is not necessarily the case. For example, students may return to an exploration stage well into their engagement if they realise that there is an aspect of the minilab they had overlooked earlier on.

It is useful to repeat the quotation in regard to the findings by Moseley *et al*. (2005) here. In that study it was reported that in problem-solving, "the cognitive components of the task do not have to be undertaken in any particular order" (see Figure 7) and that

> the three components within the cognitive skill part of the framework do not always feature in a simple linear fashion; for example, it is possible to go straight from information gathering to productive thinking, without a phase of building understanding. Although information gathering is necessary to build understanding or ensure productive thinking, it is not necessarily a simpler or less conscious process. Neither does it feature only as a first phase (stage) of an action. While most recognisable thinking process would appear to involve a series of overlapping phases (stages) involving information gathering at the outset, a gradual

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[12] It was only upon the conclusion of the developing of the proposed cyclic pattern in student group's engagement with minilabs that the findings of other researchers in this regard were considered. Consequently the observation and proposal made here is grounded in the data of the present work and was not influenced by the findings reported by other researchers.

> building of understanding and, ultimately, productive thinking, there are likely to be many occasions when learners will come to realise that they need to acquire more information or revise their initial understandings (Moseley *et al*., 2005, p. 379).

With reference to the individual’s behaviour then, the findings in the present work accord with the corresponding findings by Moseley *et al*. (2005).

As suggested by Nersessian, it is inferred that during these formulation cycles, model-based reasoning occurs in a distributed cognitive system which involves co-constructing and manipulating physical and mental models. These reasoning processes take place not just in the mind of a single student, but across the group of students who are engaged with the minilab (Nersessian, 2006). Moreover, it is also inferred that the findings by Greca and Moreira in regard to the relationship among mental, physical and mathematical models is relevant *in toto* (Greca & Moreira, 2001). If this is so, then the management of the formulation stage of the engagement is crucial from an educational point of view; and it is the stage in which the failure of the hands-on task to achieve its pedagogical goals is most likely to occur (Driver, 1983; Zohar, 2004; Abrahams & Millar 2008).

5.4.2 Suggested cyclic pattern characterising weekly problem set engagement

In considering the way in which the cyclic pattern described above may be the same as, or different from, what students would do when engaged in traditional tutorials and weekly problem sets, the cyclic pattern shown in Figure 36 was modified by removing the modelling activities that were associated exclusively with the hands-on component of the task, leaving those activities and processes that are common to solving theoretical problems and hands-on tasks. The modified cyclic pattern is shown in Figure 37, i.e., it is shown without the processes of idealisation and approximation.

It appears to be the case that when first-year physics undergraduate students engage in minilab tasks they employ the same basic set of strategies as when they are engaged with traditional (theoretical) physics problems in tutorials, problem sets, tests and exams; the difference being that when engaged in hands-on tasks, students merely add the strategies requisite for the idealisation and approximation of the observed real world. However, the solving of purely theoretical problems is not devoid of references to ‘real world’ objects which have to be incorporated into the physical model, so it may be asked where these ‘real world’ inputs come from? And it is suggested here that they are derived from a pseudo-world that is presented to the students in what could be referred to as a “sanitised exercise” (Chabay & Sherwood, 1999, p. 1045).

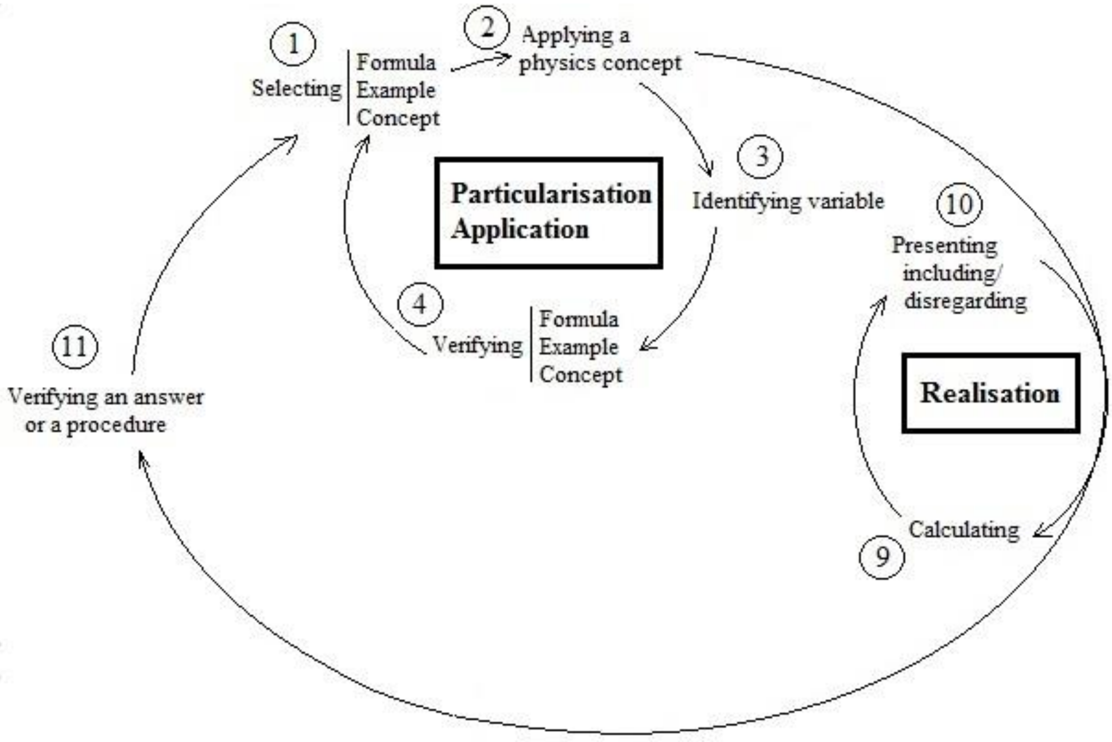

Figure 37: Suggested cyclic pattern without the hands-on component

It is suggested that, in the purely theoretical engagement, there is no *exploratory* phase equivalent to what is observed when students are engaged in a hands-on task. However, there are *formulation* and *concluding* stages that are broadly similar in both theoretical problem-solving and hands-on engagement, with the significant difference that in the theoretical case the information that goes into the physical model is derived from what could thought of as a pseudo-world.

An example of the employment of the problem-solving strategy of drawing information from a pseudo-world was observed when a number of students did not actually go to the laboratory to make any observations for minilab #5. When reviewing the conceptual models the students had submitted in writing for this minilab, it was not apparent from the answer sheets as to whether that student had made their observations in the laboratory or not, it was only when the actual observation of the real world phenomena was interrogated in an interview that it became clear as to whether the physical model that underpinned the submitted conceptual model was formulated from a real world observation or a pseudo-world observation.

The observation of a pseudo-world may be considered to be an ‘indirect’ observation and in considering the relationship that may exist between the real and pseudo-world observations, Clement’s (2009) descriptions of the formulation of analogies may be useful. Clement has proposed that analogies are predominantly formulated via a *transformation* or an *association*. In transformation the subject starts with the problem situation and transforms what they observe into a suitable analogy that is “close to” the actual problem situation. In association, the subject starts with an analogy that worked in some other, similar problem situation and then that analogy is adapted to match the present problem situation. The method of association may well result in the adopted analogy being “far from” the actual problem situation. (Clement, 2009).

In a similar way, it may well be that the information drawn into a physical model could start from either the actual idealisation and approximation of the real world, or from the sanitised idealisation and approximation of an associated, pseudo-world.

6 Conclusion

The present work, which is of an interpretivist nature, has sought to explore student strategies within a particular hands-on context. It was expected that there would emerge a narrative statement of the strategies that students adopt when modelling solutions to hands-on tasks; thereby contributing to the understanding of how modelling in a laboratory environment may be taught and learned.

For this study, a particular view of modelling, based on the Semantic View of Theories (Koponen, 2007; Greca & Moreira, 2001), has been adopted. In this model-based view of physics as proposed by Buffler *et al*. (2008), it has been posited that there are five specific processes that make up modelling *per se*, and it is these five modelling processes that have been used as a ‘lens’ through which the strategies adopted by students have been interpreted.

The backdrop to the rationale for this study is that shortcomings have been identified in what has become known as the traditional style of teaching physics (Hestenes, 1987) – *viz*., shortcomings in traditional curricula that are described by the notion that students may pass their tests with very little comprehension of what they are doing (Swan, 1951) - and it has been proposed that model-based teaching and learning (Halloun, 2007), along with inquiry-based teaching and learning (Sunal, 2004), should be taught to address this problem. To this end, the *Matter & Interactions* curriculum (Chabay & Sherwood, 1999; 2004; 2006; 2008; 2009) has made addressing this issue an expressed goal. And while curricula such as *Matter & Interactions* and Modelling Instruction (Jackson *et al*., 2008; Brewe, 2008) have met with some success, a community consensus view on definitions in modelling is still not always a given (Redish, 2003), and that the understanding of modelling itself is still being contested (Le Bihan, 2012).

Nevertheless, having adopted a particular model-based view of physics, it was taken as a point of departure that “there are particular pedagogical advantages in the view that the process of physics problem-solving occurs at the level of the physical model” (Buffler *et al*., 2008, p. 432), and therefore it is not the *realisation* of the presented conceptual model that is central to the posed research questions, but the formulation of the physical model from which the conceptual model is derived. For this reason the research questions regarding the *particularisation* and *application* of theories, and the *idealisation* and *approximation* of real world phenomena became the focus of this work.

When required to work through the processes of particularisation and application of physics theories, the findings of the present work show that the students in this sample used predominantly formula-centred strategies. This is a finding considered to be consistent with the findings of number of other researchers (e.g., Van Heuvelen, 1991; Greca & Moreira, 2001; Halloun, 2007). Not only did the students focus on finding a formula, once they had done so, the formula was used to guide every other aspect of the engagement. This suggests that students have a predominantly 'syntactic', rather than a 'semantic' understanding of theories of physics, i.e., it suggests that they can apply the rules of the formalism *F* of the theories, but do not take due cognisance of the associated rules of correspondence *R* (Jammer, 1974). That is not to say that all of the students simply have a rote understanding of physics, there certainly were examples in the data where students used semantic argument to resolve questions raised, but it suggests that from the point of view of the particularisation and application of physics theories, the physical model so formulated were generally incomplete, and therefore relatively weak, but still tenable.

When required to work through the processes of idealisation and approximation of real world phenomena, the findings of the present work show that the students in this sample used what may be referred to as 'indirect' strategies to implement these processes. The findings show that the choice of features of the apparatus that were idealised was driven by the variables that were itemised in the particularised formulae rather than by inspection of the apparatus itself. Furthermore, when a feature of the real world was observed, but which was not itemised in a particularised formula, then the students would regularly adopt what has been described herein as a 'null' strategy; i.e., the relevant feature was ignored, not because it was purposefully 'idealised to zero', but because the students did not know what to do with it. Of relevance to the processes of idealisation and approximation in hands-on tasks is the fact that students were sometimes able to submit acceptable, associated conceptual models, without idealising and approximating the relevant features of the actual apparatus at all. These were cases where students either did not go to the laboratory to engage with the apparatus, or if they did go to the laboratory, then they ignored what they had measured and presented a different set of readings. This suggests that students employ strategies of ‘observing’ some pseudo-world, which they consider sufficiently analogous to the actual one in question, and from which they can derive the ‘real world’ information that makes up the relevant physical model. Once again, this suggests that the physical model so formulated will be incomplete and therefore weak.

The findings show that students were generally proficient in working out how to use the apparatus and how to take and interpret the necessary readings. And while students were aware of the need to minimise and evaluate the uncertainty in the measurements made, they did not consider this aspect of the engagement to be important. The findings also show that students often employed the strategy of allowing one of their group to play the ‘expert’ role, but this is considered to be the employment of an epistemological resource rather than a strategy relevant to the intricacies of the modelling processes.

6.1 Limitations of the study

The most significant limitation of the present work is that it fell short in providing comprehensive answers to the second part of each of the research questions, which asked, “Why did the students adopt the strategies?”

The findings of this study, in regard to the reasons why students adopted the strategies they did, is provided in 4.1, Table 17. However, it is concluded that within the scope and context of the research instruments employed in the present work, the students were not adequately able to express the reasons for choosing the strategies they used. This limitation in the study only became apparent once the coding of the segmented data had started, which was after the interviews had taken place, and it is recognised that in order to address this research question, the research instruments needed to have a sharper focus.

The second noticeable limitation is that in 3.2 it was stated that the unit of study was the individual student - although the delimitation that the students would be working in groups was noted. At the time of deciding on the individual as the unit of study, the researcher had no sense of what the relationship between the individual and the group may be, but more importantly, there was no sense of the possibility that the study would recognise both individual cognitive processes as well as distributed cognitive processes; and while these two processes are closely intertwined, they are in fact different. As noted in the findings, in 4.4.2, by-and-large, the group dynamic is structured and predictable while the individual engagement may be quite chaotic.

It is concluded from the present work that in order to research the behaviour of an individual within a group, as was intended at the outset of the present work, it would be appropriate to do so within the ambit of complexity theory. And since the research instruments did not make accommodation for the relationship between the individual and the group, the findings do not clearly represent the strategies adopted by the individual student.

6.2 Future work

Recommendations for future work are considered from three points of view: 1) the policies that should be adopted to implement the use of hands-on tasks in the form of minilabs as described herein, 2) the practices that should be adopted, and 3) the research that should be carried out to further the understanding of the role that minilabs may play in the teaching and learning of physics.

6.2.1 Future work in regard to policy

In the opening lines to the preface of the textbook *Matter & Interactions* (3rd ed.), Chabay and Sherwood (2011) state that the offered curriculum emphasizes a perspective on introductory physics with the goal of involving students in the contemporary physics enterprise: *inter alia* by engaging students in physical modelling (idealization, approximation, assumptions, estimation). If this view is considered to be correct, and is adopted in physics teaching, then the findings of the present work suggest that policies need to be put in place to teach the processes of idealisation and approximation in modelling explicitly.

As noted in this study, the development of the skills of idealisation and approximation are complex and students do not readily come to terms with this aspect of the hands-on tasks; even though the minilabs were designed to engage them in this way. Furthermore, it is suggested that until policies are put in place that advance the requirement to teach idealisation and approximation specifically, students are more likely to continue to develop physical models of a syntactic, rather than of a semantic nature, and the status quo regarding the shortcomings identified in the traditional way of teaching physics will remain.

6.2.2 Future work in regard to practice

There was little evidence in the reviewed written submissions to suggest that the conceptual models presented by the students may have been derived from a relatively strong or a relatively weak physical model. This was illustrated in cases where students may have submitted perfectly feasible written answers, but it later emerged in the interview that they had never gone to the laboratory and had never actually observed the apparatus in the first place. The question thus arises, how were these students able to produce conceptual models that were commensurate with those of the instructor, from relatively weak physical models? It is speculated that the answer may be found in the way in which students are taught to answer questions in tutorials and weekly problem sets. As can be seen in 5.4.2 of the present work, if the observed cyclic group engagement is modified so as to remove the component that represents the engagement with the real world, then the cyclic pattern shown in Figure 37 represents the engagement with a sanitised, pseudo-world, typical of what is presented in traditional physics curricula.

From the examples of the teaching of modelling processes proposed by Justi and Gilbert (2002), Halloun (2007), Etkina and Van Heuvelen (2007) and Zwickl *et al*. (2013), in section 2.4, it can be seen that the understanding of the cyclic nature of the student engagement is not new. However, it is suggested here that the modelling processes offered by the researchers listed in 2.4 do not adequately make allowance for three aspects of the student engagement with respect to modelling: 1) the approach to modelling is too distant from what they usually learn in lectures and tutorials, 2) the epistemological resources that students apply naturally to problem solving are not adequately utilised, and 3) the questions of individual and group sense-making are not adequately addressed, i.e., the complexity whereby the individual interacts with the group is overlooked.

6.2.2.1 Incorporating modelling into everyday practice

It is suggested that even though the term ‘modelling’ is used regularly throughout the course offered to the students who were the subjects in the study, their understanding of modelling at the end of the course was not specific. This could be seen in the responses to the question “What do you think modelling is all about?” in Table 29. This suggests that for students, modelling is different, or distant, from what is done in lectures and tutorials. In some way they see modelling as a separate subject.

If this is the case – and it has yet to be shown to be so – then it may be proposed that rather than looking to teach modelling as an alternative to the traditional way of teaching physics, modelling may be successfully taught as an extension to the traditional way of teaching physics. All that is required is that the components of idealising and approximating the real world have to be taught explicitly. This implies that relevant modelling exercises and teaching materials have to be developed to meet this objective.

6.2.2.2 Using students’ epistemological resources in practice

As was suggested by Hammer and Elby (2003) with regard to ‘epistemological resources’, the findings of this study showed that the students in this sample were proficient in adopting strategies that allowed for the employment of *rule systems* by which they organised themselves and by which they applied ‘rules’ that would enable them to extract useful formulae. From these formulae they were able to itemise variables, to develop procedural steps to follow in the engagement, to check on the feasibility of the answers they had calculated, and to make corrections as and when necessary.

In the present work the findings in this regard are presented in 4.3 under the title ‘The coupling of strategies’, but these strategies actually permeate every part of the students' engagement. These strategies are also reflected in the work by other researchers such as those presented in 2.4, where, in each of the five given examples, the requirements for students to make choices, to implement those choices, and to test those choices, is present in one form or another. Giving prominence to this idea, it is of note that Halloun (2007), in Figure 4, has placed the *Evaluation* step in the very centre of the proposed model deployment flow diagram adding in the text that "every step of the way is evaluated by correspondence to the empirical situation" (Halloun, 2007, p. 674).

6.2.2.3 Considering individual and distributed cognitive engagement in practice

While not researched specifically, the findings of the present work point to the need to consider the complexity of individual and group engagement when students engage in hands-on tasks of the kind used in the present work. The findings of other research that has considered group engagement should be implemented so that the benefit of the minilab exercises can reach as many students as possible, but there is also need to consider complexity (Mitchell, 2009) in the context of hands-on engagement in its own right.

Apart from the nature of group engagement in the hands-on context, there is also a need to research the question of distributed cognitive processes and model-based reasoning (Nersessian, 2006) from the point of view of the philosophy of science. It is necessary to consider to what extent the individual mental models are reflected in the external physical model.

6.2.3 Future work in research into the formulation of the physical model

The findings of this study suggest that the process of physics problem-solving does indeed occur at the level of the physical model (Buffler *et al.*, 2008), and therefore further research of the sort undertaken by Greca and Moreira (2000; 2001) should be undertaken. However, in a study of this nature the research instruments would need to be carefully devised and applied since the question as to how students actually formulate a physical model encompasses a broad range of disciplines: psychology, pedagogy, philosophy and physics to mention a few, which suggests that such research would call for inter-disciplinary collaboration.

And although the *Matter & Interactions* (Chabay & Sherwood, 2011) curriculum offers the opportunity for students to explain and predict complex phenomena, “to make approximations, to idealize complex systems, and to think through the consequences of a particular model – activities that are central to physics but absent from the traditional curriculum” (Chabay & Sherwood, 1999, p. 1045) - the findings of this study suggests that these skills do not follow automatically. Even when the curriculum creates an expectation that modelling *per se* will be appreciated and embraced by the students, the desired outcome may not materialise. It is therefore recommended that further research be carried out to investigate how best the skills of idealisation and approximation in hands-on tasks could be taught explicitly.

Finally, rather than suggesting - as does Brewe (2008) - that there are significant philosophical differences between ‘traditional problem-solving’ and ‘the application and adaptation of models’, a synergy between these two ideas may be found by teaching, explicitly, the processes of ‘*particularisation* and *application* of theories’ and the ‘*idealisation* and *approximation* of real world phenomena’, within the framework in which students already work. It is therefore suggested that by teaching traditional physics problem-solving within the model-based view of physics posited in this study, it may be possible to meet the goals espoused by Lillian McDermott in the 1990 Millikan Lecture (McDermott, 1991).

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8 Appendix A – Sorted strategy tables

Table 30: Appendix A: Distribution of modelling processes and actions

Note: ‘End’ and ‘start’ refers to the numbering system that was used to collate the data.

Distribution of segments w.r.t. MPs

	End	Start	Num	%
NA	89	1	89	
RQ 1	135	89	46	11.2
RQ 2	228	135	93	22.6
RQ 3	294	228	66	16.1
RG 4	326	294	32	7.8
RQ 5	500	326	174	42.3
			411	100

Distribution of Actions (#1 first choice and #2 second)

Action #1 related segments

	End	Start	Num	%
Action 1	106	71	35	8.1
Action 2	146	106	40	9.3
Action 3	192	146	46	10.7
Action 4	196	192	4	0.9
Action 5	247	196	51	11.9
Action 6	323	247	76	17.7
Action 7	404	323	81	18.8
Action 8	425	404	21	4.9
Action 9	431	425	6	1.4
Action 10	468	431	37	8.6

Action #2 related segments

	End	Start	Num	%
Action 1	180	151	29	8.3
Action 2	209	180	29	8.3
Action 3	251	209	42	12.0
Action 4	271	251	20	5.7
Action 5	314	271	43	12.3
Action 6	358	314	44	12.6
Action 7	458	358	100	28.6
Action 8	476	458	18	5.1
Action 9	483	476	7	2.0
Action 10	490	483	7	2.0

Action 11	488	468	20	4.7
Action 12	501	488	13	3.0
			430	100

Action 11	500	490	10	2.9
Action 12	501	500	1	0.3
			350	100

Table 31: Appendix A: Distribution of strategies and reasons

Distribution of Strategies (Detailed)

Strategy	Strategy	End	Start	Num	%
0	No strategy applicable	86	1	85	17.0
11	Following written or verbal instructions	91	86	5	1.0
12	Following a pre-planned action	95	91	4	0.8
21	Focussing on selecting a formula	114	95	19	3.8
22	Focussing on selecting an example	122	114	8	1.6
23	Focussing on selecting a physics principle	129	122	7	1.4
31	Itemising (verbally) variables in a formula	158	129	29	5.8
32	Itemising (verbally) step/s in a procedure	231	158	73	14.6
33	Itemising (verbally) physics concepts	243	231	12	2.4
41	Announcing a value or a reading taken	270	243	27	5.4
42	Announcing the prediction of the outcome action	285	270	15	3.0
43	Announcing the result of a calculation	294	285	9	1.8
44	Announcing an observation	310	294	16	3.2
45	Announcing (asking) "what's going on", etc.	328	310	18	3.6
51	Using as a resource the text book	330	328	2	0.4
52	Using as a resource self-generated notes (incl. rough)	338	330	8	1.6
53	Using as a resource the internet as a resource	340	338	2	0.4
54	Using as a resource group members or other students	344	340	4	0.8
55	Using as a resource lecturer's class notes	347	344	3	0.6
56	Using as a resource the weekly problem sets (WPSs)	350	347	3	0.6

Distribution of Grouped Strategies

Strategy	End	Start	Num	%
0	86	1	85	17.0
10	95	86	9	1.8
20	129	95	34	6.8
30	243	129	114	22.8
40	328	243	85	17.0
50	350	328	22	4.4
60	390	350	40	8.0
70	421	390	31	6.2
81	432	421	11	2.2
82	449	432	17	3.4
91	474	449	25	5.0
92	483	474	9	1.8
93	496	483	13	2.6
94	501	496	5	1.0
			500	100

Distribution of Reasons (Detailed)

Reason	End	Start	Num	%
0	200	1	199	39.8
11	207	200	7	1.4

61	Checking on feasibility of a calculated value	355	350	5	1.0
62	Checking on feasibility of a measured value	367	355	12	2.4
63	Checking on feasibility of a procedure or an option	390	367	23	4.6
71	Guessing uncertainty in a measurement	397	390	7	1.4
72	Attempting uncertainty reduction multiple readings	409	397	12	2.4
73	Attempting uncertainty reduction working from zero	421	409	12	2.4
81	Using data selectively by ignoring readings	432	421	11	2.2
82	Adopting a 'null' solution to a problem/situation	449	432	17	3.4
91	Letting a particular student take on the 'expert' role	474	449	25	5.0
92	Simply trying something - exploring	483	474	9	1.8
93	Presenting a multi-representational solution	496	483	13	2.6
94	Announcing - that he/she is confused or "lost"	501	496	5	1.0
				500	100

12	211	207	4	0.8
13	232	211	21	4.2
14	248	232	16	3.2
15	257	248	9	1.8
31	327	257	70	14.0
32	365	327	38	7.6
33	388	365	23	4.6
34	396	388	8	1.6
41	440	396	44	8.8
42	453	440	13	2.6
61	481	453	28	5.6
71	501	481	20	4.0
			500	100

Table 32: Appendix A: Distribution of prompts and usefulness

Distribution of Reason prompts

Prompt	End	Start	Num	%
0	282	1	281	56.2
11	284	282	2	0.4
12	284	284	0	0.0
13	291	284	7	1.4
14	291	291	0	0.0
21	427	291	136	27.2
22	442	427	15	3.0
23	461	442	19	3.8
31	465	461	4	0.8
41	501	465	36	7.2

Distribution of Significant strategies

Usefulness	End	Start	Num	%
0	140	1	139	27.8
1	465	140	325	65.0
2	501	465	36	7.2
			500	100.0

500 100

Table 33: Appendix A: Distribution of actions

Distribution of RQ segments w.r.t. Actions

RQ 1 /Action related segments

	End	Start	Num	%
Action 1	114	90	24	52.2
Action 2	117	114	3	6.5
Action 3	128	117	11	23.9
Action 4	130	128	2	4.3
Action 5	131	130	1	2.2
Action 6	133	131	2	4.3
Action 7	134	133	1	2.2
Action 8	134	134	0	0.0
Action 9	135	134	1	2.2
Action 10	135	135	0	0.0
Action 11	135	135	0	0.0
Action 12	136	135	1	2.2
			46	100

RQ 2 /Action related segments

	End	Start	Num	%
Action 1	144	138	6	6.6
Action 2	176	144	32	35.2
Action 3	203	176	27	29.7
Action 4	205	203	2	2.2
Action 5	208	205	3	3.3
Action 6	227	208	19	20.9
Action 7	228	227	1	1.1
Action 8	228	228	0	0.0
Action 9	228	228	0	0.0
Action 10	228	228	0	0.0
Action 11	228	228	0	0.0
Action 12	229	228	1	1.1
			91	100

RQ 3 /Action related segments

	End	Start	Num	%
Action 1	232	230	2	3.1
Action 2	234	232	2	3.1
Action 3	234	234	0	0.0
Action 4	234	234	0	0.0
Action 5	234	234	0	0.0
Action 6	234	234	0	0.0
Action 7	234	234	0	0.0
Action 8	234	234	0	0.0

-

Action 9	239	234	5	7.7
Action 10	276	239	37	56.9
Action 11	295	276	19	29.2
Action 12	295	295	0	0.0
			65	100

RQ 4 /Action related segments

	End	Start	Num	%
Action 1	296	296	0	0.0
Action 2	296	296	0	0.0
Action 3	297	296	1	3.2
Action 4	297	297	0	0.0
Action 5	319	297	22	71.0
Action 6	319	319	0	0.0
Action 7	327	319	8	25.8
Action 8	327	327	0	0.0
Action 9	327	327	0	0.0
Action 10	327	327	0	0.0
Action 11	327	327	0	0.0
Action 12	327	327	0	0.0
			31	100

RQ 5 /Action related segments

	End	Start	Num	%
Action 1	328	328	0	0.0
Action 2	328	328	0	0.0
Action 3	333	328	5	2.9
Action 4	333	333	0	0.0
Action 5	353	333	20	11.6
Action 6	407	353	54	31.2
Action 7	477	407	70	40.5
Action 8	498	477	21	12.1
Action 9	498	498	0	0.0
Action 10	498	498	0	0.0
Action 11	499	498	1	0.6
Action 12	501	499	2	1.2
			173	100

Table 34: Appendix A: Distribution of strategies w.r.t. modelling & actions

RQ 1 /Action 1/

	End	Start	Num	%
Strategy 00	90	90	0	0.0
Strategy 10	90	90	0	0.0
Strategy 20	105	90	15	60.0
Strategy 30	109	105	4	16.0
Strategy 40	112	109	3	12.0
Strategy 50	115	112	3	12.0
Strategy 60	115	115	0	0.0
Strategy 70	115	115	0	0.0
Strategy 81	115	115	0	0.0
Strategy 82	115	115	0	0.0
Strategy 91	115	115	0	0.0
Strategy 92	115	115	0	0.0
Strategy 93	115	115	0	0.0
Strategy 94	115	115	0	0.0
			25	100

RQ 1 /Action 3/

	End	Start	Num	%
Strategy 00	118	118	0	0.0
Strategy 10	118	118	0	0.0
Strategy 20	118	118	0	0.0
Strategy 30	128	118	10	90.9
Strategy 40	128	128	0	0.0
Strategy 50	128	128	0	0.0
Strategy 60	128	128	0	0.0
Strategy 70	128	128	0	0.0
Strategy 81	129	128	1	9.1
Strategy 82	129	129	0	0.0
Strategy 91	129	129	0	0.0
Strategy 92	129	129	0	0.0
Strategy 93	129	129	0	0.0
Strategy 94	129	129	0	0.0
			11	100

RQ 2 /Action 2/

	End	Start	Num	%
Strategy 00	146	144	2	6.3
Strategy 10	146	146	0	0.0
Strategy 20	151	146	5	15.6
Strategy 30	158	151	7	21.9
Strategy 40	164	158	6	18.8
Strategy 50	172	164	8	25.0
Strategy 60	173	172	1	3.1

RQ 2 /Action 3/

	End	Start	Num	%
Strategy 00	176	176	0	0.0
Strategy 10	178	176	2	7.4
Strategy 20	182	178	4	14.8
Strategy 30	197	182	15	55.6
Strategy 40	200	197	3	11.1
Strategy 50	200	200	0	0.0
Strategy 60	203	200	3	11.1

RQ 2 /Action 6/

	End	Start	Num	%
Strategy 00	210	208	2	10.5
Strategy 10	212	210	2	10.5
Strategy 20	212	212	0	0.0
Strategy 30	224	212	12	63.2
Strategy 40	226	224	2	10.5
Strategy 50	226	226	0	0.0
Strategy 60	226	226	0	0.0

Strategy 70	173	173	0	0.0
Strategy 81	173	173	0	0.0
Strategy 82	175	173	2	6.3
Strategy 91	175	175	0	0.0
Strategy 92	175	175	0	0.0
Strategy 93	175	175	0	0.0
Strategy 94	176	175	1	3.1
			32	100

Strategy 70	203	203	0	0.0
Strategy 81	203	203	0	0.0
Strategy 82	203	203	0	0.0
Strategy 91	203	203	0	0.0
Strategy 92	203	203	0	0.0
Strategy 93	203	203	0	0.0
Strategy 94	203	203	0	0.0
			27	100

Strategy 70	227	226	1	5.3
Strategy 81	227	227	0	0.0
Strategy 82	227	227	0	0.0
Strategy 91	227	227	0	0.0
Strategy 92	227	227	0	0.0
Strategy 93	227	227	0	0.0
Strategy 94	227	227	0	0.0
			19	100

RQ 3 /Action 10/

	End	Start	Num	%
Strategy 00	244	239	5	13.5
Strategy 10	244	244	0	0.0
Strategy 20	244	244	0	0.0
Strategy 30	245	244	1	2.7
Strategy 40	245	245	0	0.0
Strategy 50	246	245	1	2.7
Strategy 60	246	246	0	0.0
Strategy 70	247	246	1	2.7
Strategy 81	256	247	9	24.3
Strategy 82	263	256	7	18.9
Strategy 91	263	263	0	0.0
Strategy 92	263	263	0	0.0
Strategy 93	276	263	13	35.1
Strategy 94	276	276	0	0.0
			37	100

RQ 3 /Action 11/

	End	Start	Num	%
Strategy 00	276	276	0	0.0
Strategy 10	276	276	0	0.0
Strategy 20	276	276	0	0.0
Strategy 30	277	276	1	5.3
Strategy 40	289	277	12	63.2
Strategy 50	291	289	2	10.5
Strategy 60	294	291	3	15.8
Strategy 70	294	294	0	0.0
Strategy 81	295	294	1	5.3
Strategy 82	295	295	0	0.0
Strategy 91	295	295	0	0.0
Strategy 92	295	295	0	0.0
Strategy 93	295	295	0	0.0
Strategy 94	295	295	0	0.0
			19	100

RQ 4 /Action 5/

	End	Start	Num	%
Strategy 00	303	296	7	30.4
Strategy 10	303	303	0	0.0
Strategy 20	303	303	0	0.0
Strategy 30	306	303	3	13.0
Strategy 40	310	306	4	17.4
Strategy 50	310	310	0	0.0
Strategy 60	315	310	5	21.7
Strategy 70	315	315	0	0.0
Strategy 81	315	315	0	0.0
Strategy 82	317	315	2	8.7
Strategy 91	318	317	1	4.3
Strategy 92	319	318	1	4.3
Strategy 93	319	319	0	0.0
Strategy 94	319	319	0	0.0
			23	100

RQ 4 /Action 7/

	End	Start	Num	%
Strategy 00	319	319	0	0.0
Strategy 10	319	319	0	0.0
Strategy 20	319	319	0	0.0
Strategy 30	322	319	3	37.5
Strategy 40	323	322	1	12.5
Strategy 50	323	323	0	0.0
Strategy 60	324	323	1	12.5
Strategy 70	327	324	3	37.5
Strategy 81	327	327	0	0.0
Strategy 82	327	327	0	0.0
Strategy 91	327	327	0	0.0
Strategy 92	327	327	0	0.0
Strategy 93	327	327	0	0.0
Strategy 94	327	327	0	0.0
			8	100

RQ 5 /Action 5/

	End	Start	Num	%
Strategy 00	336	333	3	15.0
Strategy 10	336	336	0	0.0
Strategy 20	336	336	0	0.0
Strategy 30	338	336	2	10.0
Strategy 40	344	338	6	30.0
Strategy 50	344	344	0	0.0
Strategy 60	349	344	5	25.0
Strategy 70	350	349	1	5.0

RQ 5 /Action 6/

	End	Start	Num	%
Strategy 00	359	353	6	11.1
Strategy 10	361	359	2	3.7
Strategy 20	361	361	0	0.0
Strategy 30	389	361	28	51.9
Strategy 40	394	389	5	9.3
Strategy 50	394	394	0	0.0
Strategy 60	400	394	6	11.1
Strategy 70	402	400	2	3.7

RQ 5 /Action 7/

	End	Start	Num	%
Strategy 00	408	407	1	1.4
Strategy 10	408	408	0	0.0
Strategy 20	410	408	2	2.9
Strategy 30	424	410	14	20.0
Strategy 40	453	424	29	41.4
Strategy 50	453	453	0	0.0
Strategy 60	457	453	4	5.7
Strategy 70	473	457	16	22.9

RQ 5 /Action 8/

	End	Start	Num	%
Strategy 00	479	477	2	9.5
Strategy 10	479	479	0	0.0
Strategy 20	479	479	0	0.0
Strategy 30	479	479	0	0.0
Strategy 40	486	479	7	33.3
Strategy 50	486	486	0	0.0
Strategy 60	492	486	6	28.6
Strategy 70	498	492	6	28.6

Strategy 81	350	350	0	0.0
Strategy 82	351	350	1	5.0
Strategy 91	352	351	1	5.0
Strategy 92	353	352	1	5.0
Strategy 93	353	353	0	0.0
Strategy 94	353	353	0	0.0
			20	100

Strategy 81	402	402	0	0.0
Strategy 82	402	402	0	0.0
Strategy 91	404	402	2	3.7
Strategy 92	407	404	3	5.6
Strategy 93	407	407	0	0.0
Strategy 94	407	407	0	0.0
			54	100

Strategy 81	473	473	0	0.0
Strategy 82	474	473	1	1.4
Strategy 91	476	474	2	2.9
Strategy 92	476	476	0	0.0
Strategy 93	476	476	0	0.0
Strategy 94	477	476	1	1.4
			70	100

Strategy 81	498	498	0	0.0
Strategy 82	498	498	0	0.0
Strategy 91	498	498	0	0.0
Strategy 92	498	498	0	0.0
Strategy 93	498	498	0	0.0
Strategy 94	498	498	0	0.0
			21	100

Table 35: Appendix A: Distribution of reasons w.r.t. modelling, actions and strategies

RQ 1 /Action 1/ Strategy 20/ reason

	End	Start	Num	%
Reason 00	100	90	10	66.7
Reason 11	101	100	1	6.7
Reason 12	101	101	0	0.0
Reason 13	101	101	0	0.0
Reason 14	101	101	0	0.0
Reason 15	101	101	0	0.0
Reason 31	102	101	1	6.7
Reason 32	104	102	2	13.3
Reason 33	104	104	0	0.0
Reason 34	104	104	0	0.0
Reason 41	104	104	0	0.0
Reason 42	104	104	0	0.0
Reason 61	105	104	1	6.7
Reason 71	105	105	0	0.0
			15	100

RQ 1 /Action 1/ Strategy 30/ reason

	End	Start	Num	%
Reason 00	107	105	2	50.0
Reason 11	107	107	0	0.0
Reason 12	107	107	0	0.0
Reason 13	109	107	2	50.0
Reason 14	109	109	0	0.0
Reason 15	109	109	0	0.0
Reason 31	109	109	0	0.0
Reason 32	109	109	0	0.0
Reason 33	109	109	0	0.0
Reason 34	109	109	0	0.0
Reason 41	109	109	0	0.0
Reason 42	109	109	0	0.0
Reason 61	109	109	0	0.0
Reason 71	109	109	0	0.0
			4	100

RQ 1 /Action 1/ Strategy 40/ reason

	End	Start	Num	%
Reason 00	109	109	0	0.0
Reason 11	109	109	0	0.0
Reason 12	109	109	0	0.0
Reason 13	109	109	0	0.0
Reason 14	109	109	0	0.0
Reason 15	112	109	3	100.0
Reason 31	112	112	0	0.0
Reason 32	112	112	0	0.0
Reason 33	112	112	0	0.0
Reason 34	112	112	0	0.0
Reason 41	112	112	0	0.0
Reason 42	112	112	0	0.0
Reason 61	112	112	0	0.0
Reason 71	112	112	0	0.0
			3	100

RQ 1 /Action 1/ Strategy 50/ reason

	End	Start	Num	%
Reason 00	112	112	0	0.0
Reason 11	112	112	0	0.0
Reason 12	112	112	0	0.0
Reason 13	112	112	0	0.0
Reason 14	115	112	3	100.0
Reason 15	115	115	0	0.0
Reason 31	115	115	0	0.0
Reason 32	115	115	0	0.0
Reason 33	115	115	0	0.0
Reason 34	115	115	0	0.0
Reason 41	115	115	0	0.0
Reason 42	115	115	0	0.0
Reason 61	115	115	0	0.0
Reason 71	115	115	0	0.0
			3	100

RQ 1 /Action 3/ Strategy 30/ reason

	End	Start	Num	%
Reason 00	119	118	1	10.0
Reason 11	119	119	0	0.0
Reason 12	119	119	0	0.0
Reason 13	121	119	2	20.0
Reason 14	122	121	1	10.0
Reason 15	123	122	1	10.0
Reason 31	125	123	2	20.0
Reason 32	126	125	1	10.0
Reason 33	126	126	0	0.0
Reason 34	126	126	0	0.0
Reason 41	128	126	2	20.0
Reason 42	128	128	0	0.0
Reason 61	128	128	0	0.0
Reason 71	128	128	0	0.0
			10	100

RQ 2 /Action 2/ Strategy 20/ reason

	End	Start	Num	%
Reason 00	148	146	2	40.0
Reason 11	148	148	0	0.0
Reason 12	148	148	0	0.0
Reason 13	148	148	0	0.0
Reason 14	148	148	0	0.0
Reason 15	148	148	0	0.0

RQ 2 /Action 2/ Strategy 30/ reason

	End	Start	Num	%
Reason 00	152	151	1	14.3
Reason 11	152	152	0	0.0
Reason 12	152	152	0	0.0
Reason 13	152	152	0	0.0
Reason 14	154	152	2	28.6
Reason 15	154	154	0	0.0

RQ 2 /Action 2/ Strategy 40/ reason

	End	Start	Num	%
Reason 00	158	158	0	0.0
Reason 11	158	158	0	0.0
Reason 12	158	158	0	0.0
Reason 13	158	158	0	0.0
Reason 14	158	158	0	0.0
Reason 15	158	158	0	0.0

RQ 2 /Action 2/ Strategy 50/ reason

	End	Start	Num	%
Reason 00	168	164	4	50.0
Reason 11	168	168	0	0.0
Reason 12	168	168	0	0.0
Reason 13	168	168	0	0.0
Reason 14	168	168	0	0.0
Reason 15	168	168	0	0.0

Reason 31	148	148	0	0.0
Reason 32	148	148	0	0.0
Reason 33	150	148	2	40.0
Reason 34	150	150	0	0.0
Reason 41	150	150	0	0.0
Reason 42	150	150	0	0.0
Reason 61	151	150	1	20.0
Reason 71	151	151	0	0.0
			5	100

Reason 31	156	154	2	28.6
Reason 32	156	156	0	0.0
Reason 33	157	156	1	14.3
Reason 34	157	157	0	0.0
Reason 41	158	157	1	14.3
Reason 42	158	158	0	0.0
Reason 61	158	158	0	0.0
Reason 71	158	158	0	0.0
			7	100

Reason 31	159	158	1	16.7
Reason 32	161	159	2	33.3
Reason 33	161	161	0	0.0
Reason 34	161	161	0	0.0
Reason 41	161	161	0	0.0
Reason 42	161	161	0	0.0
Reason 61	164	161	3	50.0
Reason 71	164	164	0	0.0
			6	100

Reason 31	168	168	0	0.0
Reason 32	168	168	0	0.0
Reason 33	168	168	0	0.0
Reason 34	168	168	0	0.0
Reason 41	168	168	0	0.0
Reason 42	168	168	0	0.0
Reason 61	172	168	4	50.0
Reason 71	172	172	0	0.0
			8	100

RQ 2 /Action 3/ Strategy 20/ reason

	End	Start	Num	%
Reason 00	182	178	4	100.0
Reason 11	182	182	0	0.0
Reason 12	182	182	0	0.0
Reason 13	182	182	0	0.0
Reason 14	182	182	0	0.0
Reason 15	182	182	0	0.0
Reason 31	182	182	0	0.0
Reason 32	182	182	0	0.0
Reason 33	182	182	0	0.0
Reason 34	182	182	0	0.0
Reason 41	182	182	0	0.0
Reason 42	182	182	0	0.0
Reason 61	182	182	0	0.0
Reason 71	182	182	0	0.0
			4	100

RQ 2 /Action 3/ Strategy 30/ reason

	End	Start	Num	%
Reason 00	184	182	2	13.3
Reason 11	184	184	0	0.0
Reason 12	184	184	0	0.0
Reason 13	187	184	3	20.0
Reason 14	188	187	1	6.7
Reason 15	188	188	0	0.0
Reason 31	192	188	4	26.7
Reason 32	195	192	3	20.0
Reason 33	196	195	1	6.7
Reason 34	196	196	0	0.0
Reason 41	197	196	1	6.7
Reason 42	197	197	0	0.0
Reason 61	197	197	0	0.0
Reason 71	197	197	0	0.0
			15	100

RQ 2 /Action 3/ Strategy 40/ reason

	End	Start	Num	%
Reason 00	198	197	1	33.3
Reason 11	198	198	0	0.0
Reason 12	198	198	0	0.0
Reason 13	198	198	0	0.0
Reason 14	198	198	0	0.0
Reason 15	198	198	0	0.0
Reason 31	198	198	0	0.0
Reason 32	198	198	0	0.0
Reason 33	198	198	0	0.0
Reason 34	198	198	0	0.0
Reason 41	198	198	0	0.0
Reason 42	198	198	0	0.0
Reason 61	200	198	2	66.7
Reason 71	200	200	0	0.0
			3	100

RQ 2 /Action 3/ Strategy 60/ reason

	End	Start	Num	%
Reason 00	200	200	0	0.0
Reason 11	200	200	0	0.0
Reason 12	200	200	0	0.0
Reason 13	200	200	0	0.0
Reason 14	200	200	0	0.0
Reason 15	200	200	0	0.0
Reason 31	201	200	1	33.3
Reason 32	202	201	1	33.3
Reason 33	202	202	0	0.0
Reason 34	202	202	0	0.0
Reason 41	202	202	0	0.0
Reason 42	202	202	0	0.0
Reason 61	203	202	1	33.3
Reason 71	203	203	0	0.0
			3	100

RQ 2 /Action 6/ Strategy 00/ reason

	End	Start	Num	%
Reason 00	210	208	2	100.0
Reason 11	210	210	0	0.0
Reason 12	210	210	0	0.0
Reason 13	210	210	0	0.0
Reason 14	210	210	0	0.0
Reason 15	210	210	0	0.0
Reason 31	210	210	0	0.0
Reason 32	210	210	0	0.0
Reason 33	210	210	0	0.0
Reason 34	210	210	0	0.0
Reason 41	210	210	0	0.0
Reason 42	210	210	0	0.0
Reason 61	210	210	0	0.0
Reason 71	210	210	0	0.0
			2	100

RQ 2 /Action 6/ Strategy 10/ reason

	End	Start	Num	%
Reason 00	210	210	0	0.0
Reason 11	210	210	0	0.0
Reason 12	212	210	2	100.0
Reason 13	212	212	0	0.0
Reason 14	212	212	0	0.0
Reason 15	212	212	0	0.0
Reason 31	212	212	0	0.0
Reason 32	212	212	0	0.0
Reason 33	212	212	0	0.0
Reason 34	212	212	0	0.0
Reason 41	212	212	0	0.0
Reason 42	212	212	0	0.0
Reason 61	212	212	0	0.0
Reason 71	212	212	0	0.0
			2	100

RQ 2 /Action 6/ Strategy 30/ reason

	End	Start	Num	%
Reason 00	212	212	0	0.0
Reason 11	212	212	0	0.0
Reason 12	212	212	0	0.0
Reason 13	213	212	1	8.3
Reason 14	213	213	0	0.0
Reason 15	213	213	0	0.0
Reason 31	223	213	10	83.3
Reason 32	223	223	0	0.0
Reason 33	223	223	0	0.0
Reason 34	223	223	0	0.0
Reason 41	223	223	0	0.0
Reason 42	223	223	0	0.0
Reason 61	224	223	1	8.3
Reason 71	224	224	0	0.0
			12	100

RQ 2 /Action 6/ Strategy 40/ reason

	End	Start	Num	%
Reason 00	224	224	0	0.0
Reason 11	224	224	0	0.0
Reason 12	224	224	0	0.0
Reason 13	224	224	0	0.0
Reason 14	224	224	0	0.0
Reason 15	224	224	0	0.0
Reason 31	226	224	2	100.0
Reason 32	226	226	0	0.0
Reason 33	226	226	0	0.0
Reason 34	226	226	0	0.0
Reason 41	226	226	0	0.0
Reason 42	226	226	0	0.0
Reason 61	226	226	0	0.0
Reason 71	226	226	0	0.0
			2	100

RQ 3 /Action 10/ Strategy 81/ reason

	End	Start	Num	%
Reason 00	256	247	9	100.0
Reason 11	256	256	0	0.0
Reason 12	256	256	0	0.0
Reason 13	256	256	0	0.0
Reason 14	256	256	0	0.0
Reason 15	256	256	0	0.0
Reason 31	256	256	0	0.0
Reason 32	256	256	0	0.0

RQ 3 /Action 10/ Strategy 82/ reason

	End	Start	Num	%
Reason 00	263	256	7	100.0
Reason 11	263	263	0	0.0
Reason 12	263	263	0	0.0
Reason 13	263	263	0	0.0
Reason 14	263	263	0	0.0
Reason 15	263	263	0	0.0
Reason 31	263	263	0	0.0
Reason 32	263	263	0	0.0

RQ 3 /Action 10/ Strategy 93/ reason

	End	Start	Num	%
Reason 00	273	263	10	76.9
Reason 11	273	273	0	0.0
Reason 12	273	273	0	0.0
Reason 13	273	273	0	0.0
Reason 14	273	273	0	0.0
Reason 15	273	273	0	0.0
Reason 31	273	273	0	0.0
Reason 32	273	273	0	0.0

Reason 33	256	256	0	0.0
Reason 34	256	256	0	0.0
Reason 41	256	256	0	0.0
Reason 42	256	256	0	0.0
Reason 61	256	256	0	0.0
Reason 71	256	256	0	0.0
			9	100

Reason 33	263	263	0	0.0
Reason 34	263	263	0	0.0
Reason 41	263	263	0	0.0
Reason 42	263	263	0	0.0
Reason 61	263	263	0	0.0
Reason 71	263	263	0	0.0
			7	100

Reason 33	273	273	0	0.0
Reason 34	273	273	0	0.0
Reason 41	273	273	0	0.0
Reason 42	276	273	3	23.1
Reason 61	276	276	0	0.0
Reason 71	276	276	0	0.0
			13	100

RQ 3 /Action 11/ Strategy 40/ reason

	End	Start	Num	%
Reason 00	278	277	1	8.3
Reason 11	278	278	0	0.0
Reason 12	278	278	0	0.0
Reason 13	278	278	0	0.0
Reason 14	278	278	0	0.0
Reason 15	278	278	0	0.0
Reason 31	279	278	1	8.3
Reason 32	279	279	0	0.0
Reason 33	279	279	0	0.0
Reason 34	279	279	0	0.0
Reason 41	288	279	9	75.0
Reason 42	289	288	1	8.3
Reason 61	289	289	0	0.0
Reason 71	289	289	0	0.0
			12	100

RQ 3 /Action 11/ Strategy 50/ reason

	End	Start	Num	%
Reason 00	289	289	0	0.0
Reason 11	289	289	0	0.0
Reason 12	289	289	0	0.0
Reason 13	289	289	0	0.0
Reason 14	290	289	1	50.0
Reason 15	290	290	0	0.0
Reason 31	290	290	0	0.0
Reason 32	290	290	0	0.0
Reason 33	290	290	0	0.0
Reason 34	290	290	0	0.0
Reason 41	291	290	1	50.0
Reason 42	291	291	0	0.0
Reason 61	291	291	0	0.0
Reason 71	291	291	0	0.0
			2	100

RQ 3 /Action 11/ Strategy 60/ reason

	End	Start	Num	%
Reason 00	291	291	0	0.0
Reason 11	291	291	0	0.0
Reason 12	291	291	0	0.0
Reason 13	291	291	0	0.0
Reason 14	291	291	0	0.0
Reason 15	291	291	0	0.0
Reason 31	291	291	0	0.0
Reason 32	291	291	0	0.0
Reason 33	291	291	0	0.0
Reason 34	291	291	0	0.0
Reason 41	294	291	3	100.0
Reason 42	294	294	0	0.0
Reason 61	294	294	0	0.0
Reason 71	294	294	0	0.0
			3	100

RQ 4 /Action 5/ Strategy 00/ reason

	End	Start	Num	%
Reason 00	303	296	7	100.0
Reason 11	303	303	0	0.0
Reason 12	303	303	0	0.0
Reason 13	303	303	0	0.0
Reason 14	303	303	0	0.0
Reason 15	303	303	0	0.0
Reason 31	303	303	0	0.0
Reason 32	303	303	0	0.0
Reason 33	303	303	0	0.0
Reason 34	303	303	0	0.0
Reason 41	303	303	0	0.0
Reason 42	303	303	0	0.0
Reason 61	303	303	0	0.0
Reason 71	303	303	0	0.0
			7	100

RQ 4 /Action 5/ Strategy 30/ reason

	End	Start	Num	%
Reason 00	304	303	1	33.3
Reason 11	304	304	0	0.0
Reason 12	304	304	0	0.0
Reason 13	304	304	0	0.0
Reason 14	304	304	0	0.0
Reason 15	304	304	0	0.0
Reason 31	305	304	1	33.3
Reason 32	306	305	1	33.3
Reason 33	306	306	0	0.0
Reason 34	306	306	0	0.0
Reason 41	306	306	0	0.0
Reason 42	306	306	0	0.0
Reason 61	306	306	0	0.0
Reason 71	306	306	0	0.0
			3	100

RQ 4 /Action 5/ Strategy 40/ reason

	End	Start	Num	%
Reason 00	307	306	1	25.0
Reason 11	307	307	0	0.0
Reason 12	307	307	0	0.0
Reason 13	308	307	1	25.0
Reason 14	308	308	0	0.0
Reason 15	308	308	0	0.0
Reason 31	308	308	0	0.0
Reason 32	309	308	1	25.0
Reason 33	309	309	0	0.0
Reason 34	309	309	0	0.0
Reason 41	309	309	0	0.0
Reason 42	309	309	0	0.0
Reason 61	310	309	1	25.0
Reason 71	310	310	0	0.0
			4	100

RQ 4 /Action 5/ Strategy 60/ reason

	End	Start	Num	%
Reason 00	310	310	0	0.0
Reason 11	310	310	0	0.0
Reason 12	310	310	0	0.0
Reason 13	311	310	1	20.0
Reason 14	312	311	1	20.0
Reason 15	312	312	0	0.0
Reason 31	312	312	0	0.0
Reason 32	314	312	2	40.0
Reason 33	315	314	1	20.0
Reason 34	315	315	0	0.0
Reason 41	315	315	0	0.0
Reason 42	315	315	0	0.0
Reason 61	315	315	0	0.0
Reason 71	315	315	0	0.0
			5	100

RQ 4 /Action 7/ Strategy 30/ reason

	End	Start	Num	%
Reason 00	319	319	0	0.0
Reason 11	319	319	0	0.0
Reason 12	319	319	0	0.0
Reason 13	319	319	0	0.0
Reason 14	319	319	0	0.0
Reason 15	319	319	0	0.0
Reason 31	320	319	1	33.3
Reason 32	320	320	0	0.0

RQ 4 /Action 7/ Strategy 40/ reason

	End	Start	Num	%
Reason 00	322	322	0	0.0
Reason 11	322	322	0	0.0
Reason 12	322	322	0	0.0
Reason 13	322	322	0	0.0
Reason 14	322	322	0	0.0
Reason 15	322	322	0	0.0
Reason 31	322	322	0	0.0
Reason 32	322	322	0	0.0

RQ 4 /Action 7/ Strategy 60/ reason

	End	Start	Num	%
Reason 00	323	323	0	0.0
Reason 11	323	323	0	0.0
Reason 12	323	323	0	0.0
Reason 13	323	323	0	0.0
Reason 14	323	323	0	0.0
Reason 15	323	323	0	0.0
Reason 31	323	323	0	0.0
Reason 32	323	323	0	0.0

RQ 4 /Action 7/ Strategy 70/ reason

	End	Start	Num	%
Reason 00	324	324	0	0.0
Reason 11	324	324	0	0.0
Reason 12	324	324	0	0.0
Reason 13	324	324	0	0.0
Reason 14	324	324	0	0.0
Reason 15	324	324	0	0.0
Reason 31	324	324	0	0.0
Reason 32	324	324	0	0.0

Reason 33	321	320	1	33.3
Reason 34	321	321	0	0.0
Reason 41	322	321	1	33.3
Reason 42	322	322	0	0.0
Reason 61	322	322	0	0.0
Reason 71	322	322	0	0.0
			3	100

Reason 33	322	322	0	0.0
Reason 34	322	322	0	0.0
Reason 41	322	322	0	0.0
Reason 42	322	322	0	0.0
Reason 61	323	322	1	100.0
Reason 71	323	323	0	0.0
			1	100

Reason 33	323	323	0	0.0
Reason 34	323	323	0	0.0
Reason 41	323	323	0	0.0
Reason 42	323	323	0	0.0
Reason 61	324	323	1	100.0
Reason 71	324	324	0	0.0
			1	100

Reason 33	324	324	0	0.0
Reason 34	326	324	2	66.7
Reason 41	326	326	0	0.0
Reason 42	326	326	0	0.0
Reason 61	326	326	0	0.0
Reason 71	327	326	1	33.3
			3	100

RQ 5 /Action 5/ Strategy 00/ reason

	End	Start	Num	%
Reason 00	336	333	3	100.0
Reason 11	336	336	0	0.0
Reason 12	336	336	0	0.0
Reason 13	336	336	0	0.0
Reason 14	336	336	0	0.0
Reason 15	336	336	0	0.0
Reason 31	336	336	0	0.0
Reason 32	336	336	0	0.0
Reason 33	336	336	0	0.0
Reason 34	336	336	0	0.0
Reason 41	336	336	0	0.0
Reason 42	336	336	0	0.0
Reason 61	336	336	0	0.0
Reason 71	336	336	0	0.0
			3	100

RQ 5 /Action 5/ Strategy 30/ reason

	End	Start	Num	%
Reason 00	336	336	0	0.0
Reason 11	336	336	0	0.0
Reason 12	336	336	0	0.0
Reason 13	337	336	1	50.0
Reason 14	337	337	0	0.0
Reason 15	337	337	0	0.0
Reason 31	337	337	0	0.0
Reason 32	337	337	0	0.0
Reason 33	338	337	1	50.0
Reason 34	338	338	0	0.0
Reason 41	338	338	0	0.0
Reason 42	338	338	0	0.0
Reason 61	338	338	0	0.0
Reason 71	338	338	0	0.0
			2	100

RQ 5 /Action 5/ Strategy 40/ reason

	End	Start	Num	%
Reason 00	338	338	0	0.0
Reason 11	338	338	0	0.0
Reason 12	338	338	0	0.0
Reason 13	339	338	1	16.7
Reason 14	339	339	0	0.0
Reason 15	341	339	2	33.3
Reason 31	342	341	1	16.7
Reason 32	343	342	1	16.7
Reason 33	343	343	0	0.0
Reason 34	343	343	0	0.0
Reason 41	344	343	1	16.7
Reason 42	344	344	0	0.0
Reason 61	344	344	0	0.0
Reason 71	344	344	0	0.0
			6	100

RQ 5 /Action 5/ Strategy 60/ reason

	End	Start	Num	%
Reason 00	344	344	0	0.0
Reason 11	344	344	0	0.0
Reason 12	344	344	0	0.0
Reason 13	344	344	0	0.0
Reason 14	344	344	0	0.0
Reason 15	344	344	0	0.0
Reason 31	344	344	0	0.0
Reason 32	347	344	3	60.0
Reason 33	348	347	1	20.0
Reason 34	348	348	0	0.0
Reason 41	348	348	0	0.0
Reason 42	348	348	0	0.0
Reason 61	349	348	1	20.0
Reason 71	349	349	0	0.0
			5	100

RQ 5 /Action 6/ Strategy 00/ reason

	End	Start	Num	%
Reason 00	359	353	6	100.0
Reason 11	359	359	0	0.0
Reason 12	359	359	0	0.0
Reason 13	359	359	0	0.0
Reason 14	359	359	0	0.0
Reason 15	359	359	0	0.0
Reason 31	359	359	0	0.0
Reason 32	359	359	0	0.0
Reason 33	359	359	0	0.0
Reason 34	359	359	0	0.0
Reason 41	359	359	0	0.0
Reason 42	359	359	0	0.0
Reason 61	359	359	0	0.0
Reason 71	359	359	0	0.0
			6	100

RQ 5 /Action 6/ Strategy 30/ reason

	End	Start	Num	%
Reason 00	361	361	0	0.0
Reason 11	361	361	0	0.0
Reason 12	361	361	0	0.0
Reason 13	361	361	0	0.0
Reason 14	363	361	2	7.1
Reason 15	363	363	0	0.0
Reason 31	379	363	16	57.1
Reason 32	386	379	7	25.0
Reason 33	387	386	1	3.6
Reason 34	387	387	0	0.0
Reason 41	387	387	0	0.0
Reason 42	387	387	0	0.0
Reason 61	388	387	1	3.6
Reason 71	389	388	1	3.6
			28	100

RQ 5 /Action 6/ Strategy 60/ reason

	End	Start	Num	%
Reason 00	395	394	1	16.7
Reason 11	395	395	0	0.0
Reason 12	395	395	0	0.0
Reason 13	397	395	2	33.3
Reason 14	398	397	1	16.7
Reason 15	398	398	0	0.0
Reason 31	398	398	0	0.0
Reason 32	399	398	1	16.7
Reason 33	399	399	0	0.0
Reason 34	399	399	0	0.0
Reason 41	400	399	1	16.7
Reason 42	400	400	0	0.0
Reason 61	400	400	0	0.0
Reason 71	400	400	0	0.0
			6	100

RQ 5 /Action 7/ Strategy 30/ reason

	End	Start	Num	%
Reason 00	412	410	2	14.3
Reason 11	412	412	0	0.0
Reason 12	412	412	0	0.0
Reason 13	413	412	1	7.1
Reason 14	414	413	1	7.1
Reason 15	414	414	0	0.0
Reason 31	420	414	6	42.9
Reason 32	421	420	1	7.1

RQ 5 /Action 7/ Strategy 40/ reason

	End	Start	Num	%
Reason 00	426	424	2	6.9
Reason 11	428	426	2	6.9
Reason 12	428	428	0	0.0
Reason 13	429	428	1	3.4
Reason 14	430	429	1	3.4
Reason 15	430	430	0	0.0
Reason 31	432	430	2	6.9
Reason 32	432	432	0	0.0

RQ 5 /Action 7/ Strategy 70/ reason

	End	Start	Num	%
Reason 00	458	457	1	6.3
Reason 11	458	458	0	0.0
Reason 12	458	458	0	0.0
Reason 13	458	458	0	0.0
Reason 14	458	458	0	0.0
Reason 15	458	458	0	0.0
Reason 31	458	458	0	0.0
Reason 32	458	458	0	0.0

Reason 33	421	421	0	0.0
Reason 34	421	421	0	0.0
Reason 41	424	421	3	21.4
Reason 42	424	424	0	0.0
Reason 61	424	424	0	0.0
Reason 71	424	424	0	0.0
			14	100

Reason 33	437	432	5	17.2
Reason 34	437	437	0	0.0
Reason 41	443	437	6	20.7
Reason 42	449	443	6	20.7
Reason 61	453	449	4	13.8
Reason 71	453	453	0	0.0
			29	100

Reason 33	458	458	0	0.0
Reason 34	461	458	3	18.8
Reason 41	461	461	0	0.0
Reason 42	462	461	1	6.3
Reason 61	464	462	2	12.5
Reason 71	473	464	9	56.3
			16	100

RQ 5 /Action 8/ Strategy 40/ reason

	End	Start	Num	%
Reason 00	479	479	0	0.0
Reason 11	479	479	0	0.0
Reason 12	479	479	0	0.0
Reason 13	480	479	1	14.3
Reason 14	480	480	0	0.0
Reason 15	480	480	0	0.0
Reason 31	481	480	1	14.3
Reason 32	482	481	1	14.3
Reason 33	482	482	0	0.0
Reason 34	482	482	0	0.0
Reason 41	485	482	3	42.9
Reason 42	486	485	1	14.3
Reason 61	486	486	0	0.0
Reason 71	486	486	0	0.0
			7	100

RQ 5 /Action 8/ Strategy 60/ reason

	End	Start	Num	%
Reason 00	486	486	0	0.0
Reason 11	486	486	0	0.0
Reason 12	486	486	0	0.0
Reason 13	486	486	0	0.0
Reason 14	487	486	1	16.7
Reason 15	487	487	0	0.0
Reason 31	487	487	0	0.0
Reason 32	490	487	3	50.0
Reason 33	490	490	0	0.0
Reason 34	490	490	0	0.0
Reason 41	492	490	2	33.3
Reason 42	492	492	0	0.0
Reason 61	492	492	0	0.0
Reason 71	492	492	0	0.0
			6	100

RQ 5 /Action 8/ Strategy 70/ reason

	End	Start	Num	%
Reason 00	493	492	1	16.7
Reason 11	493	493	0	0.0
Reason 12	493	493	0	0.0
Reason 13	493	493	0	0.0
Reason 14	493	493	0	0.0
Reason 15	493	493	0	0.0
Reason 31	493	493	0	0.0
Reason 32	493	493	0	0.0
Reason 33	494	493	1	16.7
Reason 34	494	494	0	0.0
Reason 41	494	494	0	0.0
Reason 42	494	494	0	0.0
Reason 61	494	494	0	0.0
Reason 71	498	494	4	66.7
			6	100

9 Appendix B – Master look-up table

Table 36: Appendix B: Extract from Master look-up table

Key:	Source #1 – Observed data Source #2 – Written data Source #3 – Interview data	Minilab # - Minilabs 1 to 7 Case # - See Table 2 location # - Time stamp on video or question #	Modelling process - Table 9 & Action - Table 10 Strategy, Reason & Prompt code - Table 11, Table 12 Usefulness code - 0 unknown, 1 useful, 2 not useful

Segment #	Source	Minilab #	Case #	location #	Student S#	***Note on context (in italics)*** **and "Transcript" or written response**	**Researcher's memo**	Modelling code	Action code #1	Action code #2	Strategy code	Reason code	Prompt code	Usefulness
1	1	6	1	00:45	42	*S42 positioned the apparatus right away, on his own.* North's in that direction (points). First thing I am going to do is to line this up along the compass needle of zero degrees so that we can measure the deflection.	S42 has given the impression that he had been primed to set the apparatus up, but has placed it in the wrong orientation. S42 has used the zero of the compass scale and not the actual north orientation. *Approximates the direction of* B_{earth}.	5	6	7	12	11	41	2
2	1	6	1	01:05	24	*S24 gestures to show the direction of the normal to the coil*. No wait, now the zero degrees is in that direction. (A short discussion ensues with S24 about the correct orientation.)	S24 suggesting that the direction of the earth's magnetic field in in an easterly direction. *Approximates direction of* B_{coil}	5	5	0	63	33	22	2
3	1	6	1	01:20	24	*Turns the apparatus to the correct orientation and then back to the incorrect orientation.* That actually doesn't matter because we just have to take the deflection.	S24 appears not to have made the connection between the orientation of the loop and the sense of where North is.	2	6	12	0	0	0	2
4	1	6	1	01:35	24	Then we will take a few readings	S24 appears to have a pre-emptive idea that a few readings are to be taken	5	7	8	72	42	0	2

5	1	6	1	01:38	42	Wouldn't it be easier if we took it from zero because…	S42 proposing a strategy for taking readings; starting from zero makes it easier	4	7	0	72	34	21	1
6	1	6	1	01:50	24	Let me turn it on to see if anything happens	S24 shows some anticipation of what to expect	0	12	0	92	0	0	1
7	1	6	1	01:55	42	*S42 & S24 Exploring the response of the apparatus*. Let's see (leans over and starts turning the voltage settings on the PSU) S24 That shouldn't change by much… and it does	S24 has made a prediction before taking the action, but the result is not what he expected	5	12	5	42	0	0	1
8	1	6	1	01:55	7	*S7 has been watching the other two for a while without engagement*. What do we measure?	S7 appears to be wishing to engage with the other students	1	3	1	31	15	0	1
9	1	6	1	02:00	42	*S42 Has repeated a question asked previously by S24, but ignored the question by S7*. Are we going to take multiple measurements?	Wishing to take multiple measurements suggests a concern with reducing uncertainty in measurement	5	8	7	72	71	21	1
10	1	6	1	02:05	24	So then we can determine the magnetic field of the coil and then…	S24 is proposing a strategy of how they should proceed *Attention is drawn by focussing on a concept*	1	6	3	32	31	0	1
11	1	6	1	02:16	42	*S42 is looking at a formula and picking on a specific item in response to S24*. Do we know the size of the loop? (By implication, the area of the loop.)	*Prompting the measurement of a variable*	1	3	6	31	13	21	1
12	1	6	1	02:20	7	*S7 also picking on a specific item in response to S24*. Do we know how many times it is coiled? (Indicates by hand)	*Promoting the measurement of a variable*	1	3	6	31	13	21	1
13	1	6	1	02:30	42	*Summarises*. so we have a loop (draws a loop), we have how much.. six volts (looking at PSU), …. magnetic field is… (pause)	S42 appears to be going through a checklist	1	1	3	31	13	21	2
14	1	6	1	02:55	42	*Turning to S24, S42 looks for a formula*. Can you remember the formula?	It has taken **3 minutes** from the start of the exercise for the question about the formula to be raised.	1	1	0	21	0	0	1
15	1	6	1	03:00	24	*S24 Having paged through his notes for some while*. So here we go, coils, N turns, (pointing to the equation) so we will need the area.	*Formula centred-strategy in operation*	1	1	3	31	0	0	1
16	1	6	1	03:10	42	*To this point S42 and S24 have ignored the other two, S7 and S39, in their group. Each pair continues to make notes and identify variables and formulas*. Mu equals NIA, we have B axis … etc. (Still without engaging	The group had been formed with two pairs of partners, meaning that the two partners in each pair had worked together before, but the individuals in the pairs had not worked together.	1	1	4	31	0	0	1

						with apparatus.)								
17	1	6	1	03:10	24	*S42 has pointed to the fact that there are two formulae written on the paper*. You can ignore this formula	Selecting a formula	1	1	0	21	32	0	1
18	1	6	1	03:45	7	*S7 Having read the task worksheet in which orientation was specified*. This thing has to be orientated so that... (turns the apparatus to its correct position) it is perpendicular to the… (shows by hand).	*Student is applying a given instruction*	2	6	0	11	12	31	1
19	1	6	1	03:45	24	*S24 responds to the action by S7 while S42 ignores what is being said.* It doesn't have to (be orientated in a particular way), we just have to measure the angle.	Neither S24 or S42 appear to have read the instruction on the worksheet regarding the requirement to orientate the apparatus in a specific way	2	6	2	0	0	0	2
20	1	6	1	03:45	7	*S7 Pointing emphatically to the notes with both first fingers*. It says over here… (he reads the instructions from the task sheet). (location# 04:05) It has to be like this… (sets up instrument)	*Appears to understand why the instrument has to be orientated in a particular way*	2	6	2	11	12	23	1
21	1	6	1	04:15	42	*S42 Pays attention to the apparatus and realises that the scale can be turned*. So then you will get a direct deflection. What you need to do is to get that between 70 and 70… you want 90 degrees	S42 seems no longer to contest the question of the orientation of the apparatus (ref 19).	5	6	7	73	34	0	1
22	1	6	1	04:25	7	What I have done is make it look as perpendicular to this (indicates with hand) as possible	S7 showing that he has worked out the correct orientation (roughly) *Aligns the apparatus acknowledging the uncertainty*	3	10	2	73	0	0	1
23	1	6	1	04:30	7	*S7 Has noted that the scale can turn*. So, can we actually turn this? (Referring to the compass)		5	6	0	73	0	0	1
24	1	6	1	04:35	42	*S42 turning the scale Sets the scale so that rest condition has the needle at 'zero'*. (Orientating it like that) makes it so much easier	The implication here is that the student means easier in that an initial reading does not have to be subtracted from a final reading	5	7	6	73	34	0	1
25	1	6	1	04:40	7	You might as well leave it on zero and we can get the deflection straight out of that	S7 appears to agree with S42 about the setting of the scale to start at zero	5	7	0	73	34	0	1
						…								

						DATA NOT INCLUDED TO MEET WORD RESTRICTION …								
460	1	4	1	24:37	9	Ja but the velocity …, doesn't it depend on…, no it doesn't	S9 seeks to justify why she would like to determine the radius of rotation of the masses but cannot.	0	2	0	0	0	0	0
461	1	4	1	24:40	9	*Ref Inc #458*. Can I do it just for my own sake? For some reason it feels very, very right	S9 gives her sense of it "feels right" as the reason for determining the radius of rotation of the masses. Neither student has actually looked at the equations they will be using to solve the given problem	0	12	0	92	0	0	0
462	1	4	1	24:45	9	*S9 takes readings of the distance of the masses from the centre shaft of the wheel*. (Holds the metre stick against the centre shaft) 14.5, (turns the wheel to the other side) should be…, 14.5		5	7	0	41	11	0	1
463	1	4	1	25:30	9	*S9 starts reading the times taken from her cell phone as S59 writes them down*. 28.42, 24.97, … , 5.67, 3.62,		5	7	0	41	42	0	1
464	1	4	1	26:40	59	*S59 is looking at the time taken per revolution as listed and makes the important observation*. Just from that (looking at the time readings) it is clear that this frictionless scene (does inverted commas by hand) isn't so frictionless	**EXAMPLE of a NULL STRATEGY:** S9 notes that there is a significant amount of friction is this system. Ref Inc #472.	4	5	0	63	33	23	1
465	1	4	1	26:48	59	Can we neglect the very small values? 'Cos technically these (referring to the list) are more accurate than that one?	S59 appears not to have made the distinction between the times before and those after dropping the masses	4	7	0	63	61	21	1
466	1	4	1	26:50	9	No, it is just the changes in them	S9 gives an explanation which may refer to the difference between the times before and those after dropping the masses, bit it is not possible for the researcher to know what she meant	2	2	6	0	0	0	0
467	1	4	1	26:55	59	*S59 expresses agreement with S9, but seems not to actually follow the reasoning*. Oh ok, ja, ja…, the changes are also different		0	0	0	91	0	0	0
468	1	4	1	27:00	9	*S9 refers to the way in which the slowing down of the wheel is to be handled*. You just need to get a basic average and you should be	S9 concluding the discussion about how to treat the times taken for each revolution of the wheel	5	7	6	32	0	0	1

						ok								
469	2	4	1	1	9	S9 included a drawing of the physics system, but did not include a vector diagram		3	10	0	93	0	0	0
470	2	4	1	1	9	S9 used four of the ten readings taken during observation in the calculation of the result	**EXAMPLE of USING OTHER DATA:** S9 had taken 10 times before and ten after but only used four before and four after in her calculations. i.e. data were used selectively	3	10	7	81	0	0	0
471	2	4	1	1	9	S9 did not use the radius of rotation of the masses, in her answer, that she had recorded in the observation	**EXAMPLE of USING OTHER DATA**: S9 had measured 14.5 cm (ref 462) but used 20.0 cm in her answer *Selective use of the data taken*	3	10	7	81	0	0	0
472	2	4	1	4	9	S9 We took the rotational axle to be frictionless 'because the friction was small enough to be neglected"	This is *in contradiction to the observation made* when taking the readings (ref 464)	3	10	5	82	0	0	0
473	2	4	1	1	59	S59 included a drawing of the physics system but did not include a vector diagram		3	10	0	93	0	0	0
474	2	4	1	1	59	S59 used four of the ten readings taken during observation in the calculation of the result	S59 had taken 10 times before and ten after but only used four before and four after in her calculations; as did S9	3	10	7	81	0	0	0
475	2	4	1	4	59	S59 had stated elsewhere in her write-up that "friction did seem to have a considerable effect" (ref 464) but went on to say that she disregarded friction "to some extent."	This is considered an unusual response for although the student indicated that they were not really sure what's to be done, friction was not included in the answer	3	10	5	82	0	0	0
476	3	0	0	01:05	59	*S59 responding to why she did such detailed minilab write-ups*. I personally like doing write-ups, so the actual experimenting part was a bit uneasy for me because I am not too great at (raising?) new concepts	**EXAMPLE of WHY DO MINILABS**: S59 did extremely detailed write-ups of all the minilabs, sometimes adding three and four pages where each answer was complete with method, etc.	3	10	0	0	0	0	0
477	3	0	0	01:16	59	But when I went home and did the write-ups it was much better for me because I could reflect on what I did and I actually learnt while I was doing the write-ups	S59 acknowledging what was observed, that she was uncertain about what to do when the minilab task was being undertaken (see Task 4 Case1) (ref 383)	3	2	0	0	0	0	0

478	3	4	1	02:50	59	*Responding the question about the observed trouble they were having in getting started with task 4, case 1.* … there was a problem…, (laughs) with the times..., like how to time the wheel	The issue of how to do the timing is related, see ref Inc #359 onwards	0	0	0	0	0	0	0
479	3	4	1	02:55	59	*Responding the question about the observed trouble they were having in getting started with task 4, case 1.* (we had a problem with whether) we should just like let the timer run and then spin the wheel for a certain number of revolutions	The issue of whether they should count the turns in a fixed time or the time for a set number of turns was related	5	6	7	0	0	0	0
480	3	4	1	03:05	59	*Responding the question about the observed trouble they were having in getting started with task 4, case 1.* (we had a problem with whether we should) assume that it (the wheel) was completely frictionless and that it would spin the same speed…, something like that	The issue of friction was related	4	5	7	0	0	0	0
481	3	4	1	05:30	59	*S59 responding to the question as to how they solved the problem of how to take the times*. She (S9) started using her cell phone (to take times) because the timers (stopwatches) were really confusing us.		5	6	7	0	0	0	0
482	3	4	1	09:16	59	*S59 in reaction to watching the observed video recorded Segment where S9 says, "assume this (the wheel) to be frictionless" (ref 426)*. I was really struggling with that in my mind because I thought the wheel, 'cos it was assumed to be frictionless (and we saw) it was not absolutely frictionless, it would actually slow down and then if you put the masses on top it would slow even more.	**EXAMPLE of EXAMPLE of IGNORING AN OBSERVATION**: It was still not clear at this stage as to whether S59 ascribed the slowing down after the weights had been added to friction or to a change in the angular momentum of the masses	2	5	0	0	0	0	0
483	3	4	1	09:43	59	*S59 responding to the prompt that they did find that the wheel slowed down and that times for fewer revolutions had to be taken*. (We had to take time for) two or three turns and then put the masses on straight away and then… (shows hand rotations)	**EXAMPLE of MAKING UP DATA**: Although S59 has reported in the interview that fewer turns were necessary, that is not what they were observed to do. The use of fewer turns appears to have been decided upon at the write-up stage. Ref Inc #444 & 455 where 10 revolutions were timed	3	10	0	81	0	0	0

484	3	4	1	09:50	59	*S59 reflecting on how the two members of their group decided on how many rotations of the wheel to time*. I think she (S9) wanted to leave it to spin like 10 times; I was struggling with that in my mind a bit.	S59 reflecting on the fact that there was some doubt as to how many turns to time	5	7	6	63	32	0	1
485	3	4	1	10:20	59	*S59 responding to the question as to whether her regular minilab partner, S9, would typically take charge of what the two of them were doing*. In the beginning yes but nowadays she does listen to me	There was no indication from other data sources that S9 did not continue to "be in charge"	0	0	0	91	0	0	0
486	3	4	1	12:45	59	*S59 responding to the question as to what made it difficult for them to make progress in doing the minilab*. (What made it difficult was) the difference of ideas (S9) was very headstrong in what she was doing and I was very headstrong in what I was doing so we were like kinda like, nudging heads (shows hands signs signifying bumping heads)	At no stage during the observation did S59 appear to understand what was actually required	0	0	0	91	0	0	0
487	3	4	1	13:05	59	*S59 responding to the question as to what made it difficult for them to make progress in doing that (Task 4 Case1) minilab*. Oh I remember, this day I didn't have my minilab sheet so usually before a minilab I would just glance through it and get a general idea of what we were supposed to do, and this time I did not have it so I was kinda lost, and (S9) had hers so I was just reading it there so I was very slow	There is no observation in the data to show that this had made any difference	0	0	0	0	0	0	0
488	3	6	0	15:30	59	*S59 responding to how she had determined the value of the resistor in minilab 6*. The colour bands…, (pointing at the resistor on the table) I think	Used an unexpected resource	0	0	0	55	0	0	0
489	3	6	0	16:20	59	*S59 responding to the question as to why she thought the uncertainty in the reading of the angle on the compass would be small*. I assumed it (the uncertainty in the reading of the angle) would be small because the graduations (on the scale) were sufficiently small (shrugs)	This method, of using the fineness if the scale has been recorded elsewhere as an indication of the smallness of the uncertainty	5	5	0	71	0	0	0

490	3	6	0	16:35	59	*S59 responding to the whether she thought friction in the compass could have had an effect*. It (the friction in the compass) probably did (have an effect) because I remember that when we were doing this that the needle kept moving…, like, even if somebody had to touch the table very lightly it would move		0	5	0	82	0	0	0
491	3	6	0	16:55	59	I probably should have considered that…	S59 had recognised the friction in the compass, and could describe its effect, but did not take it into account	0	0	0	0	0	0	0
492	3	5	0	18:50	59	*S59 responding to why she had modelled the (paper/ruler/wool minilab) as two point charges*. Because I did not know what else to do (laughs)	It is noted that this minilab did not have an easily recognisable equation that students could apply directly	2	2	1	82	0	0	0
493	3	5	0	19:10	59	S59 giving a further explanation as to why she had modelled the (paper/ruler/wool minilab) as two point charges This (two point charges) was the only one (model) I could think of without going too complex. Even now I cannot think of a better assumption		2	2	1	82	0	0	0
494	3	5	0	19:25	59	*S59 responding to the question as to whether she used the textbook a lot*. Moderately yeah..., I should perhaps use it more than I have…		0	0	0	51	0	0	0
495	3	5	0	20:00	59	*S59 when asked if she had considered using other models (for minilab 5) that could be seen in the textbook*. No…		0	0	0	0	0	0	0
496	3	5	0	20:20	59	*S59 showing how the paper was picked up when attracted by the charged ruler*. It lifted on its edge (shows by hand on the table going from horizontal to vertical position) and then it went up (moves hand up) and then it went (turns hand horizontal again)	This explanation is very clear so there was no question of S59 having observed it at the time	0	5	0	82	0	0	0
497	3	5	0	20:30	59	*S59 prompted whether it looked as if the edge of the paper was "stuck" to the table when it turned up vertically*. It looked (when it was on its edge) like it was stuck to the table with the edge like that (shows by hand) and then it was stuck to the ruler		0	5	0	82	0	0	0

498	3	5	0	21:00	59	S59 responding to being asked why, if she had noticed the way in which the paper was attracted to the charged had stood on end, she had not mentioned it in her answer. It didn't really 'click'. It didn't seem important at the time	In the thesis it is posited that the trigger to make things 'click' is generally what is prompted the associations they use and the formula that may be selected at the start of the minilab	0	5	0	82	0	0	0
499	3	0	0	21:45	59	*S59 responding to the question as to whether she had a plan as to what to do before the minilab*. Usually I don’t really think of a plan before I do (the minilabs) I just briefly peruse through the information…, (at the time)		0	0	0	12	0	0	0
500	1	7	1	00:15	23	*S23 picks up the (coil) solenoid and inspects it*. So we have to find the cross-sectional area	It is not known what has prompted this statement, but it is one typical of a strongly formula-driven strategy	1	3	0	31	0	0	1

10 Appendix C – Summary of segment categories

Of the 500 segments in the coded and truncated data set, see Table 36: Appendix B: Extract from Master look-up table, 411 segments were coded as an identifiable strategy, the balance being Segmental remarks and comments. In regard to the modelling processes, the relevant coded segment distribution showed that (approximately):

> 50% of the segments relate to particularisation, application and realisation, while 50% of the segments relate to idealisation and approximation.

In regard to the actions:

1) 10% of the segments relate to identifying variables,
2) 10% of the segments relate to observing,
3) 15% of the segments relate to taking action or agreeing on a procedure, and
4) 25% of the segments relate to measuring.

The balance of 40% of the coded segments relate to all other actions.

In regard to the strategies, excluding strategies to do with student interaction, the most significant strategies relate to:

a) selecting formulae and examples,
b) checking on the feasibility of procedures,
c) checking on the feasibility of values, either measured or calculated,
d) allowing one student to take a lead, i.e., accepting another in the 'expert role',
e) adopting a 'null' solution, i.e., ignoring observations because it was not known what to do with them, and
f) reducing uncertainty by 'setting the apparatus to zero' or taking multiple readings.

In regard to the reasons for adopting strategies, the most significant reasons relate to:

i. wanting to foster a method or a procedure,
ii. wanting to verify something; a reading, a procedure, etc.,
iii. wanting to ensure procedural correctness,
iv. wanting to find out what was happening or why something was being done,
v. wanting to correct what seemed (to them) to be incorrect, and
vi. wanting to (agreeing to) follow the lead of a group member.

While not part of the research questions, it is of interest to note that the most significant events that prompted the adoption of a strategy (decision point), see Table 32: Appendix A: Distribution of prompts and usefulness, relate to:

- a statement made by a group member,
- the completion of a measurement or a calculation, and
- an observation (generally followed by an announcement of the observation) by a group member.

And finally, while also not part of the research question, it is interesting to note that during the time in which the students are engaged in the actions and adopting strategies that are required to complete the hands-on tasks:

90% of their effort ultimately produced a useful outcome, while only
10% of the effort went down 'dead ends'.