A Case Study of a High Achiever's Learning of Physical Science

by

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Submitted in partial fulfillment of the academic
requirements for the degree of
Master of Education (Science Education) in the
School of Education, Durban
Faculty of Education
University of Natal

December 2002

ABSTRACT

This is a case study of the learning of physical science of a high achiever, selected on the assumption that instruction in learning strategies and styles used by successful learners may improve learning effectiveness of less successful learners.

Operating in an interpretive paradigm, qualitative data was gathered by participant observation aimed at sensing the complexities of the case. A rich, holistic description is given, enabling readers to form naturalistic generalisations of their own. The data corpus spans three years and is composed of audio-recorded lessons and interviews, field notes and written material. Data collection, analysis and interpretation were done in an inductive, cyclic manner, guided by research questions about learning strategies used by the learner, instructional strategies used by the teacher, and the roles played by intrinsic factors, practical work and problem solving, in contributing to effective learning of physical science by the high achiever.

The study implies that effective learning, even by the highly intelligent, involves struggle and requires the use of a variety of strategies. This fits a constructivist, rather than transmissionist, view of learning, and thus supports learner-centered transformations in South African education. The learner is interpreted to be intrinsically motivated by interest and a high regard for knowledge precision, elegance, and transferability, to use a large number of learning strategies, particularly while solving open-ended problems and performing practical investigations, in order to come to a deep understanding of physical science. The study suggests that teaching children how to learn, particularly by addressing their outlook on learning and introducing them to a variety of strategies, should be an aim of physical science instruction, and that interesting, open-ended, learner-centered tasks should be used in attempts to induce self-regulated learning.

PREFACE

The work described in this thesis was carried out in the School of Education, Durban, University of Natal, from January 2001 to December 2002 under the supervision of Dr Paul Hobden (Supervisor).

This study represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others, it is duly acknowledged in the text.

Angela Stott
December 2002

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The researcher has established close and personal relationships with the learner under study and his family members. Steps have been taken to protect anonymity of those involved. A pseudonym has been used for the learner to protect his privacy. Some minor contextual information has also been altered to protect identities. In all cases, it was judged that this information would have no influence on the interpretation of the data or findings of this study.

Dots .... Indicate pauses in the speech or sections omitted.

Citation: The source of the transcript is provided, enclosed in brackets, indicating the source, type of extract and date, e.g. (André, interview, 27/01/02).

Unless otherwise indicated, all quotes and transcripts are speakers' exact wording.

ACKNOWLEDGEMENT

I wish to thank the following people for helping me with this study:

Dr Paul Hobden, my supervisor, for arranging funding from the National Research Foundation, for putting up with a bombardment of e-mails, and for his patient, thorough, and skillful criticism and advice. I count myself privileged to have been, in language of this study, inspired by so great a teacher.

The National Research Foundation, for funding my studies.

Mr David Brookes, for advice in the initial stages of this study.

"André", for co-operation as the subject of this study, and for the many things I have learnt from him, some of which make up much of the content of this dissertation.

André's family, for consenting to conduction of this study and for supplying me with necessary information.

My parents, for more than I can ever thank them for.

Mr Radhan Moodley, for his interest and advice in this study, for "turning me upside down" and for believing in me.

Hanna, Marius, Lize and Heather, for many hours of discussion which have helped mould the thoughts given in these pages, for proofreading drafts, and for word processing help.

DEDICATION

This thesis is dedicated to my parents and my pupil.

CHAPTER 1
INTRODUCTION

1.1. Background and Rationale

> *"The mediocre teacher tells,*
> *the good teacher explains*
> *the superior teacher demonstrates*
> *and the great teacher inspires"*
> Author unknown

Since my early childhood I have wanted to teach, and to do so well. Consequently, the saying given above has often caused me to reflect on how a teacher can inspire a learner, where this suggests to me that the teacher induces the learner to extend his/her learning in a self-regulated manner. As a result of experiences recounted in this dissertation, my attention has been drawn to another aspect of inspiration, namely the learner's characteristics and strategies which enable him/her to be inspired.

In 1992 an exceptionally intelligent preschool child, whom I will call André, came to my attention. My interest in him grew over the years as his ability manifested itself, until I organised that he be removed from regular schooling for some subjects during his high school years, and that I teach him on an individual basis during some of this time. The experience of such close interaction over a period of three years with so gifted a learner has changed my thoughts on teaching, learning and intelligence immensely.

This personal alteration in outlook has coincided with changes in the South African education system with the implementation of Curriculum 2005. Traditionally, education in South Africa has been teacher and content dominated with an emphasis on preparing pupils for predictable, high-stakes examinations (Hobden, 2000; Jita, 2002; Ntshingila-Khosa, 1994). Indications of a need for change are plentiful, for example, South Africa scored well below the international average in 1999 in the Third International Mathematics and Science Study-Repeat (TIMMS-R) (Howie and Plomp, 2002). How change is successfully to be brought about is a matter of much research and debate (see, for example, Austin, *et al.*, 2002; Glover, *et al.*, 2002; Jita, 2002; Rogan, *et al.* 2002; Rollnick and Tresman, 2002). Observing André's learning has been an instrument for transformation in my teaching as a result of my undergoing a "rethink of what it means to be a learner" (Watts and Bentley, 1984, p. 312). This has made me aware of the fallacy of passive information absorption and the shortcomings of a transmission style of teaching (Leonard, *et al.*, 2002). Beyond this, it has drawn my attention to manners of thought which are powerful in André's learning, enabling him to be inspired, i.e. to be able to be stimulated to undergo self-regulated learning. I believe that some of these could be incorporated into new approaches to teaching physical science in South African schools, particularly during this period of transformation, to raise learning effectiveness.

1.2. Research approach

This is a case study of an individual learner, selected for study because of the interest I have in his learning as a result of his high achievement and because of my belief, supported by literature, that less successful learners can be helped to improve their learning by being instructed in the use of learning strategies and styles employed by more successful learners (Baron, 1985, 1987; Gerace, 1993; Sternberg, 1987). The data corpus spans three years and is composed of audio-recorded lessons and interviews, field notes, and written material. This qualitative data was gathered by participant observation, since, operating in an interpretive paradigm, a human instrument is considered best able to sense and examine the complexities of the case, and thus generate a rich, holistic description from which readers can make naturalistic interpretations and generalisations of their own (Merriam, 1988; Stake 1994). Data collection, analysis, and interpretation were done in a reflective, inductive, cyclic manner, resulting in descriptive and interpretive analyses which are grounded in the data (Taber, 2000).

Data collection and analysis were guided by the general question and associated specific sub-questions:
What are the general characteristics of a high achiever's effective learning of physical science?

a) What strategies are used in the effective learning of physical science by a high achiever?
b) What roles do practical work and problem solving play?
c) What instructional strategies on the part of the teacher contribute to effective learning?
d) What intrinsic factors contribute to effective learning?

1.3. Theoretical Referents

1.3.1. Introduction

My understanding of terms central to this study, together with a summary of my theoretical framework and questions arising from it, are given below.

1.3.2. High achiever

I interpret the term high achiever as referring to a learner who has ability and performance components, corresponding to Burden's (1979) term gifted. However, I prefer the term high achiever since it suggests clearer identification on the basis of performance than does the term gifted. Burden gives an IQ of 130 as a minimum for classification in the high ability group. In the absence of IQ information, other indications of intelligence can be used. Solomon (1979) gives transfer of knowledge to new contexts and a high capacity for information complexity, and Baron (1985, 1987) and Jensen (1987) name superior mental processing and use of beneficial learning strategies and styles, as diagnostic of high ability. In my opinion, André fits this description. This is testified to by the high marks he achieves for mathematics, physical science and computer studies work beyond his chronological grade level at school, the complex hardware and software designs he has created, and the prestigious academic accolades he has earned, such as national awards for physics, electronics and computer programming projects and mathematics and physical science olympiads. Consequently, following Denton and Postlethwaite's (1984) nomenclature, I can confidently refer to him as a high achiever in the specific subject areas of physical science, mathematics, computer programming and electronics.

1.3.3. Learning

In this study I have adopted the view that studying experts in action can inform our understanding of the learning process (Gerace, 1992), and that intelligence can be raised through the teaching of beneficial learning strategies and styles, identified by observing the learning of successful learners (Baron, 1985, 1987; Sternberg, 1987). While initial data collection and analysis were done in an exploratory manner, my later focusing questions and interpretation of learning effectiveness are rooted in Conceptual Change Theory (CCT) (Dykstra, *et al.*, 1992; Hewson, 1996; Hewson and

Lemberger, 2001) and the Information Processing Model of Learning (IPM) (Gagné, 1985; Glynn, *et al.*, 1995; Mayer, 1988). Additionally, Schoenfeld's Framework for the Analysis of Problem Solving in Mathematics (Schoenfeld, 1985), is borrowed for analysing learning behaviour. The components of successful problem solving identified in this framework are: resources, heuristics, control and belief systems. In the light of this, learning is seen to involve selection and use of resources and learning strategies (heuristics) by metacognitive control processes affected by the learner's belief system.

According to the Information Processing Model of Learning, relationship formation, i.e. learning, occurs in the mind's working memory, which is of very limited capacity, and consequently, selection of relevant resources to be brought to and utilised in the working memory during the formation of scientifically sound and beneficial conceptual relationships, is a limiting factor in learning (Gagné, 1985; Niaz and Logie, 1993). An aim which emerged during focusing of this study has been the identification and analysis of strategies the high achiever uses to reduce limitations of this factor during his learning of physical science.

According to CCT, learning is viewed from a constructivist perspective (Kramer, 1999), and thus is seen to involve an individual's construction of knowledge from perceptions arrived at by personal interpretation of information (Cobern, 1995), where decisions concerning conceptual change are guided by judgements about conceptual status (i.e. intelligibility, plausibility and fruitfulness) (Hewson and Lemberger, 2001). However, given the personal and contextual aspects of determination of intelligibility, plausibility and fruitfulness, this model describes how people learn, rather than how they should learn. An aim which emerged during focusing of this study has been the identification of aspects of the learner's belief system which steer conceptual change in the high achiever's learning of physical science such that a concept's intelligibility, plausibility and fruitfulness are considered raised once a scientifically more accurate understanding has been reached.

1.4. Structure of dissertation

After discussing my theoretical framework of effective learning, I describe and motivate my research approach. Then I provide a description, followed by analytical and interpretative discussions, of the high achiever's learning of physical science. I close with a summary of findings and suggestions concerning implications of this study.

In the literature review discussed in Chapter Two I look at learning, effective learning, and obstacles to effective learning. In the discussion on research methodology in Chapter Three, I motivate study of the particular case, motivate use of the research design I have utilised, discuss the study's validity and reliability and its limitations, and I describe how I collected, analysed and interpreted data. In Chapter Four I describe the learning of the high achiever under study, and in Chapter Five I interpret and analyse this learning by supplying assertions in answer to the study's research questions. I end, in Chapter Six, with a summary, a discussion of the limitations of the study and suggestions of implications of this work.

CHAPTER 2

EFFECTIVE LEARNING OF PHYSICAL SCIENCE: A THEORETICAL FRAMEWORK

2.1. Introduction

This chapter aims at situating this study within the existing understanding of learning by providing a literature-based theoretical framework with which data analysis and interpretation have been approached. This begins with an overview, in the form of an analogy, of the view I have taken of learning. I then go into more detail about learning, effective learning, and some of the obstacles to the effective learning of physical science.

2.2. An analogy: learning and carpentry

The analogy given below, in which I liken learning to carpentry, is borrowed, partially, from Gagné (1985), and illustrated in Figure 2.1 on p. 7.

The pieces of wood chosen for assembly are like propositions (pieces of information) selected for combination in learning. The tools used to connect components together are likened to learning strategies which enable relationship formation between propositions. Selection of appropriate components and tools, and decisions about how these should be used and how much time and effort should be devoted to the task, are under the control of the carpenter and are determined by his selection, combination and control skills and his criteria for product acceptability. Similarly, learning strategy selection and use is controlled by metacognitive processes which are determined by the learner's belief system.

The shelves around the workbench contain tools and building materials. They represent the learner's long term memory (LTM). However, the carpenter can only combine objects when they are on his workbench, which is relatively small. Similarly, the formation of relationships, i.e. learning, can only occur in the mind's short term memory (STM), also called working memory, the capacity of which is very limited. In the picture some objects are falling off the workbench, representing information loss due to overload in the working memory. Stacking and compact packing of items can reduce this.

If the carpenter considers objects for combination to be poorly matched, he may reject the combination or alter one or more of them until he believes that they are fit to be joined. Similarly, a learner combines pieces of information he believes to be compatible. This may require alteration of conceptions (accommodation) before acceptance into knowledge systems (assimilation).

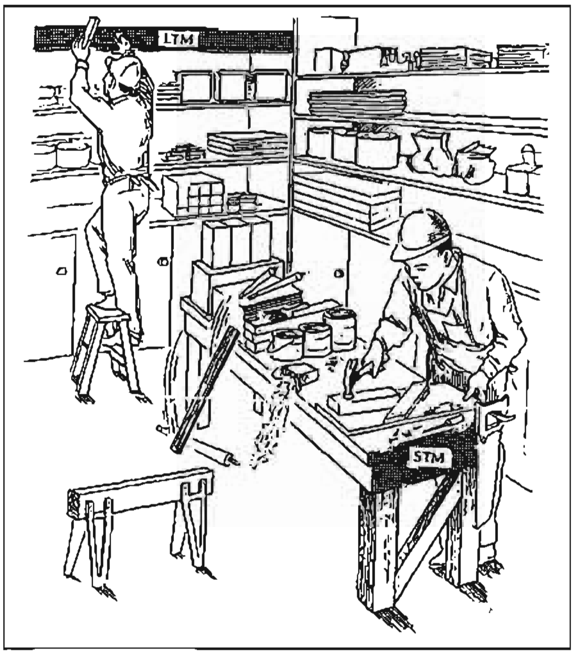


Figure 2.1 An analogy: working memory serves as a workbench during learning. (From Klatzky, in Gagnē, 1985)

2.3. How do people learn?

I use both Conceptual Change Theory (CCT) (Dykstra, *et al.*, 1992; Hewson, 1996; Hewson and Lemberger, 2001) and the Information Processing Model of Learning (IPM) (Gagné, 1985; Glynn, *et al.*, 1995; Mayer, 1988) to understand learning since I believe that these two models complement one another. In my opinion, a weakness of the IPM is its possible suggestion that knowledge can be absorbed. CCT, on the other hand, stresses construction of knowledge through accommodation and assimilation. On the other hand, I consider a strength of the IPM to be its explanation of cognitive overload through the limited capacity of the working memory, which is not accounted for by CCT.

2.3.1. Conceptual Change Theory

Conceptual Change Theory (CCT) is based on the assumption that individuals construct their knowledge as a result of personal choices they make, and is therefore constructivistic in nature (Kramer, 1999). Constructivists view all learning as the individual's construction of knowledge from perceptions arrived at through personal interpretation of information using existing knowledge and sense-making strategies (Cobern, 1995; Wheatley, 1995). Therefore, learning is seen to be an active process on the part of learners, with prior learning playing a significant role in learning. While teachers may be able to influence learners, it is considered to be the learners' choices which determine what will be constructed in their minds.

> A constructivist view of learning perceives students as active learners who come to science lessons already holding ideas about natural phenomena, which they use to make sense of everyday experiences. Learning science, therefore, involves students in not only adopting new ideas, but also in modifying or abandoning their pre-existing ones. Such a process is one in which learners actively make sense of the world by constructing meanings. (Scott, cited in Moodley, 2000, p.15)

CCT suggests how knowledge is constructed and what influences a learner's choices during this construction (Hewson and Lemberger, 2001).

Piaget's terms assimilation and accommodation are often used in describing conceptual change. These are explained below as given by Dykstra, *et al.* (1992). Assimilation is the recognition that information fits the learner's existing conception, and includes selectively ignoring discrepancies which are not considered diagnostic of the concept. Accommodation is the alteration of a previously held conception. This results from disequilibration (conceptual dissatisfaction) experienced by learners on confrontation with information which is inconsistent with their knowledge structures. Hewson (1996) identifies two types of conceptual change which occur in learning: conceptual exchange, which corresponds to accommodation, and conceptual enlargement, involving relatively easy learning by making connections to what is already known, i.e. assimilation without need for prior accommodation. The processes of assimilation and accommodation are represented in figure 2.2 on the following page.

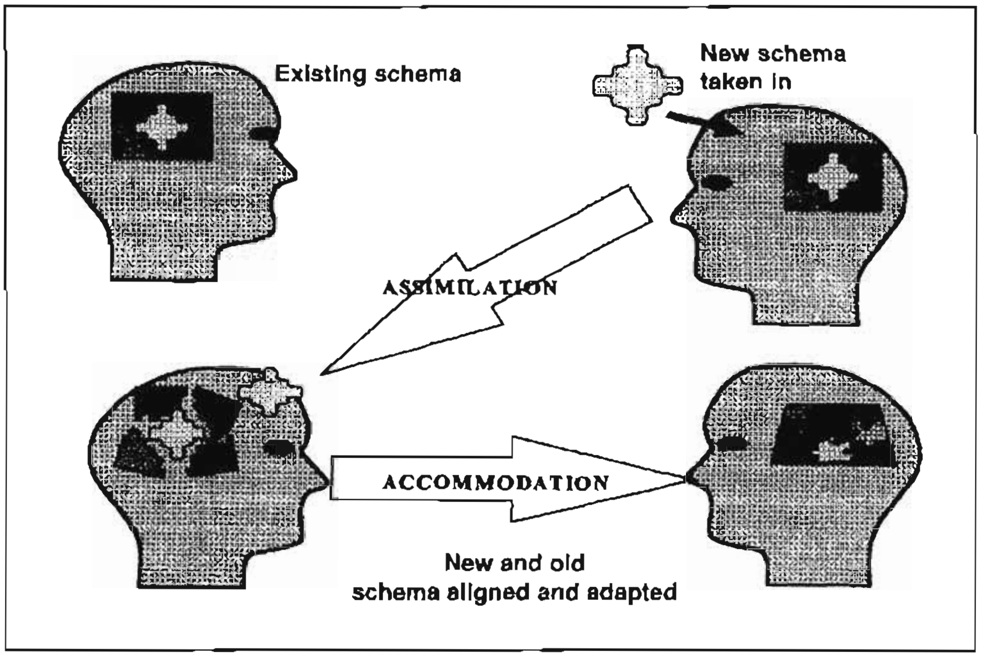


Figure 2.2 Diagrammatic illustration of the processes of assimilation and accommodation. (From Kramer, 1999, p.8)

However, this model shown in the diagram above is too simplistic to explain learners' possession of multiple versions of a concept, each of which is resorted to under specific contextual conditions, hence the idea of conceptual status, as determined by the individual's perception of the intelligibility, plausibility and fruitfulness of the concept within a specific context, has been incorporated into CCT (Hewson, 1996; Hewson and Lemberger, 2001). However, noting the individual's and context's roles in determining the criteria of conceptual status, the model tells us how people learn, but not how they should learn. I suggest that the next step is to determine the characteristics which should be valued by a learner of physical science to ensure consideration of scientifically sound conceptions as having a higher status than alternative conceptions, regardless of context, and hence enable scientifically sound conceptual choices to be made both inside and outside the classroom.

2.3.2. The Information Processing Model of Learning

Figure 2.3, given on the following page and taken from Mayer (1988), summarises the Information Processing Model of Learning. I regard its main value to be the attention it draws to the role of the short term memory's (STM's) limited capacity in learning.

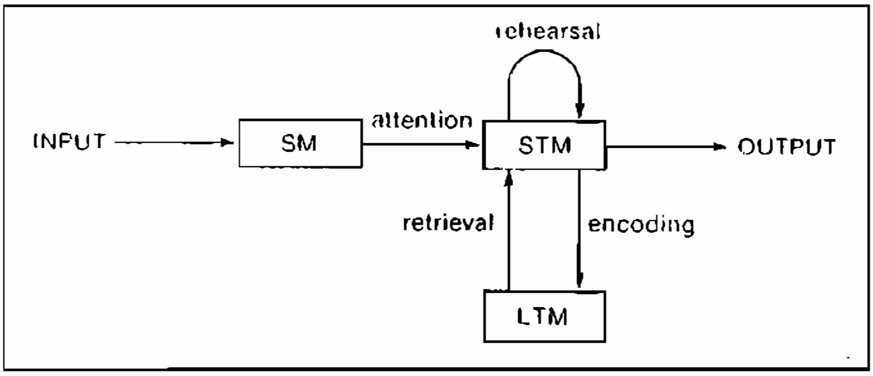


Figure 2.3 Schematic representation of the human information processing system. (From Mayer, 1988, p. 15)

According to this model, some of the information presented to a person's extremely short sensory memory (SM) is selected by attention being paid to it, and this is passed on to the short term memory (STM) where it is lost after a short time if not rehearsed During rehearsal, links are formed within the components of this new knowledge. While the new knowledge is in the STM, pre-existing knowledge may be accessed from the long term memory (LTM) and, during a process of comparison and evaluation, transformations may occur either in the new knowledge, or the pre-existing knowledge, or both. Links between the new and prior knowledge are formed. The new knowledge may then be stored in the LTM within a knowledge schema. This may be accessed and brought into the STM for output at a later stage.

The capacity of the STM (also called working memory), is considered by many authors to be the limiting factor in learning (Niaz and Logie, 1993). James Clerk Maxwell recognised its importance in the 19th century: "I quite admit that mental energy is limited ... and efforts of attention would be much less fatiguing if the disturbing force of mental distraction could be removed" (reprinted in Niaz and Logie, 1993, p. 511). Abilities to remove irrelevant information from working memory, routinise, categorise, cluster and chunk knowledge, reduce cognitive load by freeing up space in the STM (Lipman, 1991; Oberauer, 2001; Stevenson and Palmer, 1994). However, the learner's ability to respond with flexibility to novel situations may be sacrificed by these processes (Lavoie, 1995). Cognitive flexibility is ensured by formation of a large number of links between and within the learner's procedural (process) and declarative (factual) knowledge (Lavoie, 1995). These links, however, can only be formed when elements are represented simultaneously in working memory (Gagné, 1985, Oberauer, 2001).

2.3.3. Summary

I view learning as a process in which knowledge is constructed through the formation of perceptions resulting from the learner's interpretation of information. I consider two factors to be particularly influential in affecting learning outcome, as given by CCT and the IPM respectively. Firstly, learners' criteria for higher intelligibility, plausibility and fruitfulness (i.e. status) of a concept in a particular context will guide their conceptual choices. Secondly, the condition for simultaneous representation of knowledge elements in the low capacity short term memory, in order for relationship formation to occur, is a limiting factor in learning. CCT and the IPM describe learning. I now turn to effective learning.

2.4. What is effective learning?

2.4.1. Learning for understanding

It appears to me that the terms learning for understanding, quality learning, effective learning and meaningful learning (e.g Ausubel in Stanton, 1990a; Gerace, 1992; Hauslein and Smith, 1995; Larkin, 1985; Novak and Gowin, 1984; Stevenson and Palmer, 1994; Willis, 1993) all refer to learning which involves a two-way evaluation process between new and prior knowledge, resulting in modification of either or both of these and integration of the new information into a conceptual schema, thus making the knowledge usable. In other words, learning for understanding involves conceptual change. Willis (1993) cites Bowden's statement that quality learning is about:

> searching for meaning, developing understanding and relating that understanding to the world around. As a consequence, the world is seen differently and student conceptions have undergone change. Quality learning is about conceptual change - seeing the world differently is an essential outcome. (Bowden, cited in Willis, 1993, p. 391)

According to Hewson and Lemberger (2001) "Coming to a deep understanding of a conception … means grappling with the conditions of intelligibility, plausibility and fruitfulness that define a conception's status." (p. 123). The word grappling suggests an active, effortful, individual process, a view expressed in the next quotation as well:

> Understanding a text isn't a gift from someone else. It requires patience and commitment from those who find it problematic. To study is not to consume ideas. Study is a form of reinvention, recreating, rewriting, and this is a subject's, not an object's choice. (Freire, cited in Moodley, 2000, p. 10)

So learning for understanding can be viewed as being an effortful process of conceptual change. However, there are degrees and types of effort and various possible outcomes of conceptual change, so I now turn the discussion to depth of learner engagement during learning for understanding.

2.4.2. Depth of learner engagement

Moodley (2000) uses the terms actual, representational, and notional to describe levels of engagement with information during learning. He represents this in the manner given in figure 2.4 on page 13. Engagement with material on the actual level involves using the original words of the information source. For learners to be able to exert the freedom to express this information in their own form, i.e. to operate on the representational level, a degree of understanding needs to be reached. Even deeper engagement by the learner, on the micro- and hyper- levels, i.e. on levels of greater specificity and generality respectively, develops an understanding of details within the information, and of the concepts, theories, or laws of which the information forms a part. The learner is then said to be operating on the notional level of engagement in learning.

Bruner (1971) stresses the importance of theory formation in learning, "Knowledge, to be useful, must be compact, accessible, and manipulative. Theory is the form that has these properties." (p. 106). This appears to correspond with the view that engagement with information on the hyper-level reduces cognitive load by enabling much information to be represented in little space within the short term memory. Bruner refers to this as avoiding clutter, which he labels lethal in learning since very little knowledge can be dealt with at one time by the human mind. "A concept or the connected body of concepts that is a theory is man's only means of getting a lot into the narrow compass of his attention all at one time. Without some such aid, there is clutter." (Bruner, 1971, p. 123).

While the value of operation on the micro-level cannot be understood in terms of reduction of space taken in working memory, I view its purpose to be clarification of meaning, particularly for the purpose of enabling the learner to undergo the synthesis, analysis, evaluation and subsumption involved with operation on the hyper-level of engagement. These processes are associated with a deep learning style which employs use of higher order thought (Schmeck, 1988; Willis, 1993), to which I now turn.

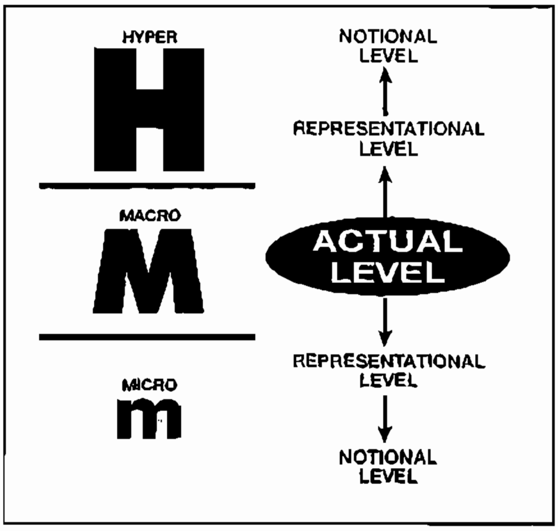


Figure 2.4 Learner engagement levels. (From Moodley, 2000, p.26)

2.4.3. Higher order thought

There is some discrepancy in the literature as to how to refer to, categorise and define the type of thought which may be referred to as higher order. For example, Lipman (1991) refers to excellent thinking as having three components: critical, complex and creative thought, while it appears that Resnick's (1987) use of the term higher order thinking and Hobden's (2002) reference to critical thought are both applied to a combination of all three of the components identified by Lipman. Resnick says that while this type of thought is difficult to define, it is easy to recognise. Higher order thinking is non-algorithmic, tends to be complex, and often yields multiple solutions, each with costs and benefits. It involves nuanced judgement and interpretation, the application of multiple criteria, uncertainty, self regulation of the thinking process, imposing meaning in apparent disorder, and is effortful.

Authors such as Wilson and Nickerson, both cited in Hobden (2002), motivate the teaching of higher order thinking skills by referring to the need for a flexible, teachable workforce in order to meet the needs of a society undergoing rapid technological changes. Willis (1993) speaks of higher order learning and says that this leads to longer term retention, greater flexibility and higher intrinsic motivation than does "the reproductive learning of factual material" (p. 385). Schmeck (1988) defines learning as "a by-product of thinking, the tracks left behind by our thought. We learn by thinking, and the quality of the learning outcome is determined by the quality of our thoughts." (p. 171).

Therefore, thought, particularly higher order thought, is clearly central to effective learning. However, as Schuster (1992) puts it, "There is a fascinating complexity to thinking, a mixture of chaos and coherence, knowledge and intuition." (p. 160), and so some approach is needed for dissection and analysis of effective thought, and thus effective learning. I have chosen to borrow Schoenfeld's Framework for the Analysis of Problem Solving Behaviour in Mathematics (from Schoenfeld, 1985), for this purpose.

2.4.4. Schoenfeld's Framework

I now turn to the components of effective thinking, and hence effective learning, the outcome of which is development of a deep understanding.

Woods (1988) equates problem solving strategies with learning strategies due to their mutual employment of higher order thinking to make sense of unknown situations, and Lavoie (1995) and Wheatley (1995) refer to learning as a problem solving activity. Consequently, I consider it reasonable to analyse learning using a framework for understanding problem solving behaviour. This opinion is strengthened by the finding that much learning of physical science in South African schools is focused on problem solution (Hobden, 2000). Consequently, I have chosen to structure my discussion on higher order thought using Schoenfeld's Framework for the Analysis of Problem Solving in Mathematics (from Schoenfeld, 1985). According to this, problem solving behaviour is determined by the individual's resources, heuristics, control and belief system.

Resources

The difference in performance of expert and novice problem solvers lies in the nature, structure and utilisation of their stored knowledge, with experts having extensive and highly organised knowledge structures which they draw heavily on during qualitative analysis of problem situations (Gerace, 1992; Hauslein and Smith, 1995; Leonard *et* *al.*, 1996; Snyder, 2000; Willson, 1995). These authors identify the relationships between, and organisation of, elements as particularly important, with experts showing a high degree of clustering and linking, and hierarchical activation of knowledge.

Gick and Holyoak, and Hasselhorn and Korkel, cited in Lipman (1991), suggest that the majority of school children and undergraduate students generally fail to deliberately use prior knowledge when confronted with a new situation. This suggests the importance of not only possessing appropriate prior conceptual and procedural knowledge, but also owning and using strategies necessary for utilisation of this knowledge.

Stevenson and Palmer (1994) and Willis (1993) maintain that learning for understanding generates intrinsic motivation because new knowledge becomes meaningfully integrated into cognitive schemas, providing a satisfaction which the fragmentary storage involved in rote learning does not. This suggests that the extent to which prior knowledge can be used affects the belief system of the learner.

So it can be seen from the above that it is generally accepted that resources are vital in learning, the mental organisation of these resources affect their usefulness, and their usefulness is further affected by and affects the other components of learning.

Heuristics; Learning strategies

Schoenfeld (1985) classifies automated strategies as resources and those which require conscious thought as heuristics. This shows correspondence with Garner's (1988) definition of learning strategies as sequences of activities, largely under the deliberate, conscious control of the learner, which are selected from alternative activities in order to attain a learning goal. However, given the difficulty in knowing whether observed learning activities are performed consciously or not, I use the term learning strategies to refer to observable patterns of behaviour, controlled consciously or subconsciously by the learner, which serve as tools for learning to occur.

Schmeck (1988) considers effective learning strategies to be "those that have the greatest impact on our thought processes" (p. 171). Interpreting thinking quality in terms of levels of engagement with material, as given in Figure 2.4 on page 13, aids understanding of the value of learning strategies associated with a deep learning style. Such strategies include categorisation, comparison and contrast, hierarchical organisation of ideas in networks, and abstraction (Schmeck, 1988), and thus involve learners engaging with information at the representational and notional levels. In contrast, the surface learner repetitively rehearses information with little to no translation from the form the information is given in, i.e. the learner remains at the actual level of engagement.

Interpreting learning for understanding to mean undergoing conceptual change, I would expect effective learning strategies to :

- find new or accommodated forms of knowledge which may be acceptable for encoding, i.e. for assimilation.
- evaluate whether accommodation is necessary before assimilation can occur, through comparison of new and prior knowledge using personal standards of status evaluation.
- form and strengthen conceptual links, thus causing and reinforcing the process of assimilation, through combination of knowledge elements.

This bears resemblance to Sternberg's (1987) classification of learning strategies as strategies of selective encoding, selective comparison, and selective combination.

Baron (1985, 1987) and Sternberg (1987) advocate improvement of intelligence through instruction in beneficial learning strategies. However, research shows that knowledge of and ability to use a strategy is insufficient to ensure that it will be applied where appropriate. Chi (1985) found that there is a complex interaction between the use of a strategy and the amount and structure of the content knowledge (resources) to which the strategy is to be applied. Reynolds and Shirey (1988) and Schoenfeld (1985) highlight the importance of metacognitive strategies (control), while Palmer and Goetz (1988) point to the importance of motivation (belief system) in selection and use of appropriate learning strategies.

This discussion shows that learning strategies are very important for effective learning, but they are insufficient on their own due to their interaction with the other components of learning.

Control

By control, Schoenfeld (1985) refers to self-regulation of activity through selection and implementation of resources and strategies. It involves planning, monitoring and assessment, decision-making and conscious metacognitive acts. In reference to the important role control plays in problem solving, Schoenfeld states: "The issue for students is often not how efficiently they will use the relevant resources potentially at their disposal. It is whether they will allow themselves access to those resources at all" (p. 13), and Resnick (1987), referring to the need for control in learning, says "many individuals primarily lack good judgment regarding when strategies should be applied" (p. 26).

In reference to the components of an ability to control learning, McCombs (1988), identifies metacognitive skills as being important: "The self-controlled and self-motivated learner is one who can plan, regulate, and evaluate his or her own skills and strategies" (p.142). A number of authors (e.g. Forrest-Pressley and Gillies, cited in Garner, 1988; Lipman, 1991; Stevenson and Palmer, 1994) refer to the importance of metacognition in learning. Bandura and Schunk, cited in McCombs (1988) assert that the metacognitive act of self-evaluation against internal standards allows learners to create self-incentives which, when fulfilled, result in satisfaction, which causes interest and an enhancement in self-efficacy.

Thomas, cited in McCombs (1988), relates control in learning to the learner's beliefs about learning:

> It seems reasonable to assert that the spontaneous use of learning strategies is a matter of disposition: the disposition to perceive a learning task as controllable, to feel responsible for the outcome, and to search actively for ideas for solving the problem posed by the task. (p. 144)

Carver and Schuer, cited in Butler and Winne (1995), also refer to the interaction between the control learners exert in their learning and their beliefs about learning, saying that self-regulated learning occurs when learners stumble on obstacles which they consider themselves able to surmount. Moodley (2000) says self-regulated learning occurs when a learner escapes from the pedagogical cycle propelled by extrinsic motivation from the teacher, to undergo learning propelled by the learner's intrinsic motivation, as illustrated in figure 2.5 on the following page.

It appears to me that the views given above are all embedded in self efficacy theory, which has to do with learners' beliefs about their abilities relative to task demands (McCombs, 1988; Moodley, 2000; Palmer and Goertz, 1988). I conclude, therefore, that the control learners exert on their learning determines strategy and resource usage and is significantly influenced by their belief systems, to which I now turn.

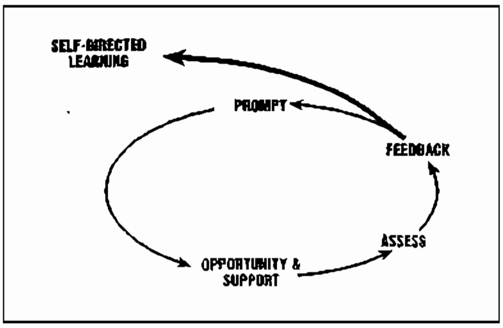


Figure 2.5 Path to the attainment of learner autonomy. (From Moodley, 2000, p. 13)

Belief system

Schoenfeld (1985) defines a learner's belief system as "the set of (not necessarily conscious) determinants of an individual's behaviour" (p. 15). He states that "problem-solving performance is not simply the product of what the students know; it is also a function of their perceptions of that knowledge, derived from their experiences" (p. 14), in other words, it is a function of their belief systems. Figure 2.6, taken from Moodley (2000), illustrates a relationship between learning performance and learner perceptions, showing the amount of invested mental effort (AIME) learners are prepared to allocate to learning as being optimal when their perceived self efficacy (PSE) or the perceived task demand characteristics (PDC) is neither low nor high. In other words, when learners perceive their capabilities (self efficacy) either to be high or low in relation to the demand of the task, then they will expend less mental effort in the task than if they perceive it to be challenging but within the range of their capabilities. This corresponds to Vygotsky's theory that optimal learning occurs in the individual learner's zone of proximal development (Lee and Smagorinsky, 2000).

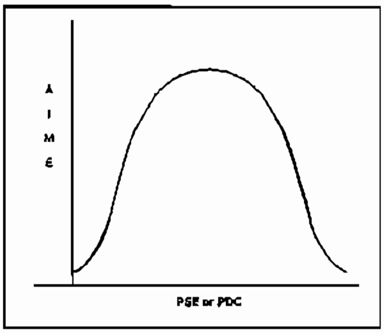


Figure 2.6 Relationship between AIME and PSE or PDC.
(From Moodley, 2000, p.21)

Learners' perceptions of relevance and interest in the material to be learnt determine the perceived value of the learning outcome, an additional factor affecting the amount of mental energy they are prepared to invest in learning (Moodley, 2000).

The discussion so far has explained the values of intrinsic and extrinsic motivation in learning in terms of self efficacy theory. Another way of looking at this is that motivation increases the size of the functional mental capacity, which is the portion of the working memory which is utilised (Pascual-Leone, cited in Niaz and Logie, 1993). According to this model, highly motivated learners are able to learn more effectively than less motivated learners because of the greater space motivation makes available for use in the short-term memory.

Learners' beliefs about learning do not only affect how much effort they apply to their learning, but also the direction of the conceptual choices they make. Learners choose to undergo conceptual change if they perceive a new concept to be more intelligible, plausible or fruitful than their existing conception (Hewson and Lemberger, 2001). This suggests a powerful role played by learners' beliefs concerning criteria for intelligibility, plausibility and fruitfulness in determining the outcome of their learning.

In summary, I view the learner's belief system to be the fundamental component of learning in that it determines the extent and direction of learning. I believe that this view corresponds with Baron's (1985) assertion that the fundamental component of intelligence is learning style, which is determined by the individual's personality and outlook, i.e. by his belief system. The two main learning styles are generally given as deep and surface (Sharwood, 2000; Schmeck, 1988; Woods, 1998). Baron (1985, 1987) says that while the teaching of learning strategies is easier to do than are attempts to alter personality-embedded learning styles, the high number and low general transferability of beneficial strategies reduce the likelihood of strategy instruction causing a general improvement in intelligence, whereas the cultivation of beneficial learning styles, like the cultivation of good morals, builds a better learner, and a better person:

> I would thus argue that the teaching of intelligence is part of the teaching of character. In teaching people to think well, we are trying to maintain and extend certain intellectual standards, much in the way we maintain moral standards in teaching other kinds of conduct. (Baron, 1987, p. 56)

2.4.5. Summary

I view effective learning of physical science to be that which results in possession of a deep understanding, as is evidenced by employment of higher order thought during an interaction with the learning material on the notional level of engagement. I think that this is brought about by use of resources and learning strategies in a manner which enables reduction of the limitation caused by the low capacity of the mind's working memory, and which brings about scientifically sound conceptual change, which requires possession of scientifically compatible criteria for conceptual intelligibility, plausibility and fruitfulness. I view effective learning, as described above, to result from learners exerting productive control over their learning because of the interest and motivation which arise from a positive belief system towards physical science learning.

2.5. Obstacles to effective learning

After having discussed what I understand by effectiveness in learning, I now turn to a few obstacles which hinder learning, particularly scientifically sound learning of physical science and optimal learning by intelligent children. I look at the fallacy of conceptual learning through inductive practical discovery, gaps in communication, and what researchers into education of gifted children call the stint.

2.5.1. The fallacy of conceptual learning through inductive practical discovery

A constructivist view of learning rejects the notion of absorption of information from observations, since observations must be converted to perceptions through interpretation (Cobern, 1995), which is done using prior knowledge, expectation, and imagination (Driver, 1983):

> Science is not just a collection of laws, a catalogue of facts, it is a creation of the human mind with its freely invented ideas and concepts. Physical theories try to form a picture of reality and to establish its connections with the wide world of sense impressions. (Einstein and Infeld, cited in Driver, 1983, p. 3)

Hence, Driver calls conceptual learning of science through inductive practical discovery "a fallacy" (p. 3). Lock (1990) also refers to the general need for teacher control during data interpretation when conceptual understanding is the focus of instruction. This means that communication, by means of which learners may be directed to view observations in the way scientists do, is important in learning. However, communication has very real limitations, as discussed below.

2.5.2. Communication gaps

I find figure 2.7, below, developed by Moodley (2000), useful for understanding communication gaps and the role of dialogue in learning. It illustrates that the teacher's instruction lights up certain conceptions in the teacher's mind and certain conceptions in the learner's mind. However, only a few of these overlap and therefore meaning is shared only to an extent. The degree by which understanding is not shared describes the pedagogical gap. Through dialogue, the likelihood of increasing the extent of shared meaning, and hence narrowing the pedagogical gap, rises. The persistence of students' intuitive beliefs and the frequent alteration of their conceptions in directions unintended by the instruction which causes this alteration (Gauld, 1989), is partially explained by and partially explains the existence and significance of the pedagogical gap, particularly in a traditional classroom where transmission-style lecturing is the sole means of instruction (Leonard, *et al.*, 2002).

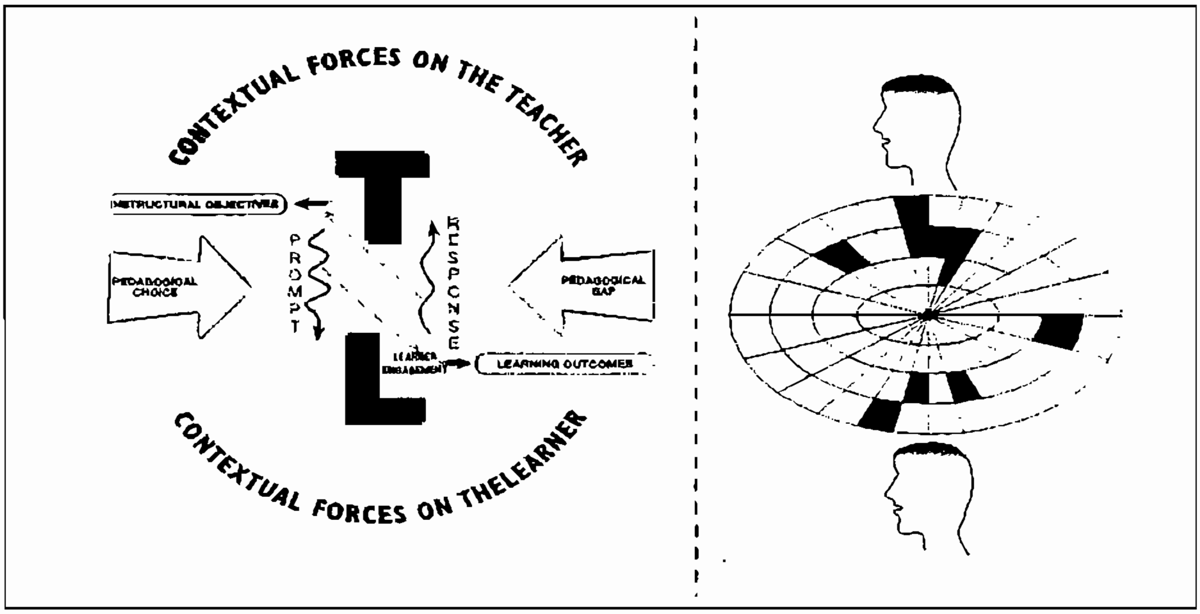


Figure 2.7 Diagrammatic representation of teacher-learner dialogue and the pedagogical gap. (From Moodley, 2000, p.12)

2.5.3. The stint

Learners of high ability frequently suffer from the stint, i.e. they stifle their precocity in order to conform to normal standards of expectation, thus preventing high achievement (Bridges, 1980; Burden, 1979; Stanley, 1979; Watkinson, 1981). To prevent this, several authors suggest more use of open-ended tasks and non-direct instruction for the gifted than is used in mainstream teaching (Cicchelli, 1985; Gowan *et al.*, 1979; Hauck *et al.*, 1972; Kagan, 1988; Renzulli, 1979).

2.5.4. Summary

Formation of scientifically sound conceptions is hindered by the existence of gaps in communication, where communication is a necessary component of learning, given the limited scientifically sound learning that occurs from children's individual practical discovery. Additionally, effective learning by gifted children is often hindered by pressure to conform to lower standards of expectation than they are capable of achieving.

2.6. Conclusion

I view learning as a process in which knowledge is constructed through the formation of perceptions resulting from the learner's interpretation of information. I consider two factors to be particularly influential in affecting learning outcome. Firstly, learners' criteria for higher intelligibility, plausibility and fruitfulness (i.e. status) of a concept in a particular context will guide their conceptual choices. Secondly, the condition for simultaneous representation of knowledge elements in the low capacity short term memory, in order for relationship formation to occur, is a limiting factor in learning.

I view effective learning of physical science to be that which results in possession of a deep understanding, as is evidenced by employment of higher order thinking during an interaction with the learning material on the notional level of engagement. I think that this is brought about by use of resources and learning strategies in a manner which enables reduction of the limitation caused by the low capacity of the mind's working memory, and which brings about scientifically sound conceptual change, which requires possession of scientifically compatible criteria for conceptual intelligibility, plausibility and fruitfulness. I view effective learning, as described above, to result from learners exerting productive control over their learning because of the interest and motivation which arise from a positive belief system towards physical science learning.

Formation of scientifically sound conceptions is hindered by the existence of gaps in communication, where communication is a necessary component of learning, given the limited scientifically sound learning that occurs from children's individual practical discovery. Additionally, effective learning by gifted children is often hindered by pressure to conform to lower standards of expectation than they are capable of achieving.

It is with these views about learning, effective learning, and obstacles to effective learning, that I have approached the research of this study, to which I now turn.

CHAPTER 3
RESEARCH METHODOLOGY

3.1. Introduction

In this chapter I describe and motivate the research activities I carried out during the course of this study. Qualitative data was collected, largely through participant observation of a single student's learning of physical science, and this was subjected to inductive analysis. The case study was conducted within an interpretive research paradigm.

The following general question and associated sub-questions guided the collection and analysis of data:

What are the characteristics of a high achiever's effective learning of physical science?

a) What strategies are used in the effective learning of physical science by the high achiever?
b) What roles do practical work and problem solving play?
c) What instructional strategies on the part of the teacher contribute to effective learning?
d) What intrinsic factors contribute to effective learning?

I begin by introducing and motivating choice of the particular case, then I explain how the research design is suitable for answering the questions given above, I describe methods used to ensure validity and reliability, and, finally, I outline my research activities.

3.2. The particular case

Stake (1994) identifies three types of case studies, classified according to the researcher's purpose in performing the study. Two of these, the intrinsic and instrumental case studies, between which there is no clear line of distinction, correspond with my view of this study. The purpose of the intrinsic case study is to understand the particular case for its own sake because it is intrinsically interesting. The main reasons I have chosen this particular child for study are the access I have to observing his learning and the interest I have in his learning as a result of the peculiarity of his high achievement. Despite, and also as a result of, the uniqueness of the case, I do also view this study as potentially having instrumental value, i.e. that it may "facilitate our understanding of something else" (Stake, 1994, p. 237), namely an understanding of effective learning of physical science. This is based on an assumption, supported by literature, that observing successful learners in action can aid our understanding of how to help less successful learners to improve performance (Baron, 1985, 1987; Gerace, 1993; Sternberg, 1987). Expert-novice research in problem solving is also based on this premise (Gerace, 1993; Hauslein and Smith, 1995; Leonard *et al.*, 2002; Maloney, 1994; Snyder, 2000; Watts, 1994; Woods, 1988).

The subject of this case study, whom I refer to in this dissertation as André, comes from a middle-class, Afrikaans family. He has attended the private, rural, mission school at which I teach since he was in grade R. The majority of the approximately 400 pupils in the school come from rural Zulu backgrounds. In 2002 he was in grade 10, doing nine examinable subjects, only two of which he was taught in a mainstream class. For the other subjects he received individual tuition or facilitation. My contact with him includes having taught him Physical Science on an individual basis for the past three years. André has shown exceptional intelligence from a very young age. This has particularly manifested itself in national awards he has earned himself in the areas of mathematics, physical science, electronics and computer programming over the past three years.

3.3. Fit of research design to research questions

The purpose of this study has been to reach an holistic understanding of the high achiever's learning in his normal learning context. A research design which uses qualitative data and inductive analysis to generate a thick description (Geertz, cited in Stake, 1994) and interpretive generalisations, is suited to this purpose for a number of reasons. A descriptive case study catches unique features which would be lost in research involving a larger number of subjects, is easily understandable, and is open to alternative interpretation by readers, thus extending its value beyond the researcher's interpretations (Adelman, cited in Bassey, 1999; Cohen, *et al.*, 2000; Stake, 1994). The researcher's observation, synthesising, analytical and interpretive activities, are central to such a study, allowing the detection of non-verbal aspects to which only a human instrument is sensitive (Bogdan and Biklen, 1982; Merriam, 1988).

Dependence on the researcher as an information channel is consistent with an interpretive world-view, which states that since it is not possible to obtain a single objective truth, human interpretation is useful in approaching an understanding of some of the multiple facets of reality. Operating within this paradigm is suitable for a naturalistic study where it is neither possible nor desirable to control for variables (Merriam, 1988).

Taber (2000) says that "studies of a phenomenon as subtle and complex as the learning of science require in-depth examination of individual learners" (p. 469), and Roth (1998) refers to studies which "display examples of learning processes *in vivo*" as able to "contribute to understandings of physics learning processes" in a manner which is "accessible to the teaching community" (p. 1019). These remarks point to the value of a study such as this one, as well as motivating the in-depth, *in vivo* approach of observing a single learner's learning when seeking to answer questions about the learning process.

3.4. Validity and reliability

3.4.1. Internal validity

Internal validity refers to the extent to which findings are congruent with reality. Since qualitative research is embedded in an interpretive paradigm, judging internal validity rests on the investigator's demonstration "that he or she has represented those multiple constructions adequately, that the reconstructions ... are credible to the constructors of the original multiple realities" (Lincoln and Guba, cited in Merriam, 1988, p. 286). Long-term observation and triangulation (Merriam, 1988) were used to ensure internal validity. Relevant sections of the descriptive chapter were shown to the people to which they refer, and appropriate adjustments were made to ensure valid representation. In all cases this only required minor changes to my original descriptions.

3.4.2. Reliability

Lincoln and Guba (cited in Merriam, 1988) refer to dependability and consistency of data as the qualitative equivalent of reliability. Walker (cited in Merriam, 1988) says that in a case study this involves "presentation of material in forms where it is open to multiple interpretations" (p. 44). Consequently, I have provided detailed descriptions to allow readers the opportunity to construct their own interpretations. Triangulation and making the audit trail explicit (Merriam, 1988) are also techniques I have used to ensure reliability.

3.4.3. External validity

External validity refers to the generalisability of the study to other situations. However, a case study is done in order to understand the particular in depth rather than for the purpose of generalisation. While a case study may be a small step towards formation or confirmation of grand generalisation (Campbell, cited in Stake, 1994), a number of authors express the opinion that there are ways of looking at generalisation which place case studies in a more favourable light than does a positivist understanding of the term. Bassey (2000) speaks of fuzzy generalisations, which predict possible occurrences in situations similar to the case. This seems to correspond with the suggestion by Cronbach, cited in Merriam (1988), that, given the need to assess and incorporate the weight of local conditions, the concept of working hypotheses should replace that of generalisation in social science research. Erickson (cited in Merriam, 1988), states the following concerning interpretive case study research:

> The search is not for abstract universals arrived at by statistical generalisations from a sample to a population, but for concrete universals arrived at by studying a specific case in great detail and then comparing it with other cases studied in equally great detail. (p. 130)

Thus, the general can be found in the particular, and the particular is manifested in the concrete in the qualitative case study. This relationship between general and particular is referred to by Simons, cited in Bassey (2000):

> The tension between the study of the unique and the need to generalise is necessary to reveal both the unique and the universal and the unity of that understanding. To live with ambiguity, to challenge certainty, to creatively encounter, is to arrive, eventually, at "seeing anew". (p. 36)

Coming to see anew corresponds, I believe, with Stake's (1994) reference to formation of naturalistic generalisations by the reader. He argues that, since understanding is socially constructed, the reader of a case study forms his own generalisations from the virtual experience of participating in the life of the case. Consequently, a description sufficiently rich for the reader to form interpretations is important in the case study report (Gallagher and Tobin, 1991; Kennedy, cited in Merriam, 1988; Stake, 1994; Stenhouse, cited in Bassey, 2000). I have attempted to produce such a description in Chapter Four.

3.5. Limitations and ethics in research activities

Given the intricacy of learning, a major challenge to this study has been the formation of valid *petite généralisations* (Stake in Bassey, 1999), i.e. general statements about the student's learning, from complex situations. However, large amounts of data were collected in a variety of manners, thus improving validity of emergence of patterns of behaviour.

Throughout the study I have placed more importance on maintenance of a good learning environment and working relationship with the child than on gathering data, and this has meant sacrifice of data collection in a few cases. Other ethical considerations included obtaining parental permission prior to conduction of the study, and pseudonym use to preserve anonymity. The learner himself was not told the nature of the study until after most of the data was in, although he did agree to being interviewed and was aware of audio-recordings of lessons. This was done to limit interference in the natural context of learning. He did, however, on being told about the research, give his consent to being the subject of the study.

3.6. Data collection procedures

3.6.1. Data gathering

Data was intentionally gathered for this study over a period of two years. However, some data is also available from the year prior to the start of the study, and therefore the data corpus spans three years. Data was collected in the form of audio-recorded lessons and interviews, field notes, which include detailed lesson reports, diary entries of critical incidents and records of personal communications, written comments, and formal and informal samples of work. Initial data was gathered in an exploratory manner, with data collection becoming more focused in the final year.

3.6.2. Data corpus

Table 3.1 summarises the data corpus, giving the year of collection and quantity of each data type gathered.

Table 3.1 Relationship between type of data gathered, quantity and year of collection.

	2000	2001	2002	Total
Audio recorded lessons	**8**	**5**	**4**	**17**
Detailed lesson reports (field notes)	**0**	**35**	**0**	**35**
Diary entries: critical incidents and comments (field notes)	**0**	**0**	**21**	**21**
Interviews:	**0**	**1**	**14**	**15**
1. *with learner:*				
a) audio-recorded			4	4
b) summarised from personal communication		1	3	4
2. *with others*				
a) letter written in response to open ended questions I supplied			2	2
b) summarised from personal communication			5	5
Written data from the learner	**0**	**19**	**8**	**27**
a) rough work produced while thinking during lessons		17		17
b) voluntarily supplied, self-directed work		2	1	3
c) work produced formally for school			6	6
d) note about his views			1	1

3.7. Research cycles and data transformation

Bogdan and Biklen (1992) and Merriam (1988) state that data analysis should be an ongoing process during data collection, to be intensified once the data is all in.

I used various methods to help me manage and analyse the data. These included coding, as illustrated in Appendices A and B, sorting, an example of which is provided in Appendix C, mind-mapping, given in Appendix D, and model-forming, as in Appendices E and F. These activities were performed throughout the two years in which data was continuously collected, resulting in gradual focusing from an exploratory start. During the course of writing this dissertation, further data was collected, and further selection and categorisation was done, guided by the focusing associated with the discipline of writing up the study.

The research is grounded in its data since it was not approached with a hypothesis for testing, as is the case in experimental studies. Rather, a theoretical framework emerged through an internal dialogue resulting from cycles of data collection, analysis and literature review (Bogdan and Biklen, 1982; Taber, 2000).

3.8. Conclusion

This is a case study of an individual learner, selected for study because of the interest I have in his learning as a result of his high achievement and because of my belief, supported by the literature, that less successful learners can be helped to improve their learning by being instructed in the use of learning strategies and styles used by more successful learners. Qualitative data was gathered by participant observation, since, operating in an interpretive paradigm, a human instrument is considered best able to sense and examine the complexities of the case, and thus generate an holistic description. The data corpus spans three years and is composed of audio-recorded lessons and interviews, field notes and written material. Data collection, analysis and interpretation were done in a reflective, cyclic manner, resulting in descriptions and interpretation which are grounded in the data (Taber, 2000). A rich description is now given, in Chapter Four, with the purpose of enabling readers to form naturalistic generalisations of their own (Stake, 1994). This is followed by my analysis and interpretation, in Chapter Five, using the theoretical framework given in Chapter Two.

CHAPTER 4

DESCRIPTION: ANDRÉ AND HIS LEARNING

4.1. Introduction

This chapter starts with information about André's background and school environment with the purpose of placing the focus of this study, namely André's learning of physical science, in context. The description of André's physical science learning begins with an overview of his learning program, followed by the description of a single physical science lesson, which is used as a springboard for discussing André's general behaviour while learning physical science.

4.2. General context

4.2.1. Background

Introduction

André was born, in 1986, into a middle class, Afrikaans family. He has two sisters who are 5 and 6 years older than him respectively. Both his parents are professionals. André stays with his mother, his father living overseas. To an extent, André's intelligence was recognised from an early age, particularly by his grandmother. She noticed that André, at four, could understand arithmetic concepts which only the brightest children in the grade one class she taught managed to grasp.

A reflective, inquiring introvert

André's father says that at a young age he was "very quiet - exceedingly so at times" (André's father, written comment, 19/04/02). His sisters comment that he would, even at preschool age, sit by himself, thinking, and sometimes making remarks such as what fraction of a quarter of an hour was left before a certain time. His mother reports that he lived in his own dream world when he was little and once he could read he would often lock himself up in the bathroom with a book. Also, he would spend a lot of time experimenting: systematically investigating bubble production during dish washing and swinging a bucket around when he should have been hanging washing up, for example. She says he enjoyed making patterns, such as positioning cutlery on the table in symmetrical, balancing arrangements. His father remembers finding André, at a very young age, engrossed in studying the mechanics of a clock.

Formation of intuitive conceptions

It appears (interview, 29/01/02) that André has formed many scientifically sound conceptions by observing every-day events, listening to people, and, later, reading. He remarked that he inferred the meaning of the term momentum from his sister's use of the word before he was in school. He says that "things which cause amazement" have made him think about scientific principles and perform thought experiments. An example he gives is his mother's comment, when he was about four, that there is no up or down in space. He says he thought about force and motion in space and consequently performed thought experiments where friction is absent. When asked about the relationship between his early intuitive learning and later formal learning, he replied:

> you have a vague something of the concept but maybe integrated into this many other things and then when you get a term for it and learn what it is then you learn how to separate it and treat it as a concept. It's interacting with other things but that further causes you to understand the concept better: once you know there is actually such a thing. (André, interview, 29/01/02)

My involvement: an introduction

Besides teaching André in grade R, my first experience of his ability was when, at age 10, he entered the Expo for Young Scientists competition for the first time. I allowed him to work on his construction in my laboratory and noticed that he paid great attention to precision, and frequently lost himself for considerable periods of time in investigation, repeatedly performing an operation to obtain greater accuracy. The perseverance he showed was, in my experience, exceptional for his age.

Besides contact with him in his subsequent projects, I occasionally invited him to work with equipment in my laboratory over the next few years. I saw that he possessed highly advanced spatial and number concepts and an intuitive conceptual understanding of physics which far surpassed my own. He would often try to design perpetual machines, and then set himself the task of explaining how they violated the law of conservation of energy. I recall that he referred to rates of change, made use of analogies, proportional reasoning, deduction and induction, during these early sessions.

Since André entered high school, in 2000, I have been teaching him on an individual basis. I also have a large amount of extracurricular contact with him and his family.

Extra-curricular learning and accolades

André went through a brief stage of building simple electric circuits while in the first school grades. At eleven he was exposed to reading material on electronics, which initiated conceptual circuit designing, although he was only exposed to physical circuit building a year later. His grade seven Science Expo project was the first of his high achievements, winning him a gold medal on national level. This was followed by a series of complex electronics projects which have earned him gold medals at national level each year to the present and have won him invitations to spend time in the electronics and physics departments of the University of Natal. In addition, he has received awards on provincial and national levels for mathematics and science olympiads during this period. The lecturer who has mentored André's recent electronics learning has this to say about André:

> When I first met him he was in grade seven and involved with some elementary analog and digital electronic circuitry. His understanding and knowledge of these components was self gained and was at a level that would have been appropriate for a grade 12 student taking the practical electronics course. He had not had any exposure to programmable logic. During the December vacation of 2000 André spent some time on the NU campus and was involved with building up some electronic kits relating to a weather satellite project run by the School of Electrical, Electronic and Computer Engineering. His performance and ability to understand electronic concepts was equivalent to some of our second year electronic engineering students. I then gave him a text book that is used by third year electronic engineering students as a first course in micro-controller programming and system design. This is a course that contains five hours of lectures per week over a 13 week period. André read the book on his own and taught himself how to use the 8051 micro-controller in less than two weeks. At the end of this period he was completing tasks that the students would be attempting at the end of the course. The most recent project that I have seen from André (the soccer robot) is of a level that I would expect from a good third or fourth year electronic engineering student. Given his age, André is one of the most enthusiastic and intelligent students that I have had the pleasure to work with in my six years of university experience. I have not had the opportunity to assess his breadth of knowledge relating to the other subjects required at university level. All comments are thus restricted to the mentioned areas of the field of electronics. (Electronics lecturer, written comment, 25/10/02)

4.2.2. School context

André's school and André's class

André has attended a private school situated on a mission station in a rural area of Kwa Zulu Natal since grade R. Selection for admission is not done on an academic basis. In 2002 André was one of eight boys in a grade 10 class of 27 learners, one member (himself) having an Afrikaans background, one German, one English, one Sotho, two Botswanan, and the remainder Zulu. The teachers are drawn to the school primarily for serving on the mission station, and therefore a significant portion lack formal teaching qualifications.

André's specific learning context

Throughout André's primary schooling he attended normal classes. In 2000 and 2001 he received individual, advanced, tuition for General Science and facilitation for Mathematics. In 2002, he took nine examinable subjects: English I, Afrikaans II, German III, Mathematics, Physical Science, Biology, Geography, Computer Studies and Technika Electronics, but only attended regular classes for English and German. For the remainder, André received individual tuition or facilitation from four teachers who have voluntarily taken responsibility for André's learning beyond their normal teaching loads. André's 2002 timetable is given in Appendix G. In general, except for the three languages, he writes exams of grades at least one higher than his chronological level, which, in 2002, was grade 10.

Learning subjects other than physical science

At times André's emotional detachment from learning biology and geography, which I teach him individually in addition to physical science, is so great that he answers only questions he is asked and does so extremely briefly, volunteers no information, shows no enjoyment or sense of humour and does nothing to affect the course of the lesson. While such extreme behaviour is not experienced very often, André's learning of these subjects rarely approaches the excitement and mental activity of his learning of physical science. Also, he will occasionally be somewhat vague when speaking about topics to do with biology and geography, which I have never observed to be the case for physical science.

His other teachers report to me that André often challenges and debates little details. His Computer Studies and Mathematics teachers say, emphatically, that he does not accept things at face value, but his language teachers comment that this is not always the case. Some of his teachers say he sometimes fails to, or seems not to want to, comprehend or remember simple instructions which are easily grasped by other members of the class. Except for his English teachers, who report that occasionally he does not do his work or produces relatively poor work, particularly when he seems to perceive a question to be silly, his teachers report that his work is of a high standard. Except for Computer Studies and Mathematics, however, the teachers would not call him exceptional in their subjects. They also say that he is not particularly diligent, except his German teacher, who comments that he works hard at learning grammar rules. André's English teachers report that he "has his days" when he particularly shows disinterest. They also say that his work is always concise, he does only what is required, and he is always looking for short cuts.

His Mathematics facilitator, who spends little time teaching him directly, says that her style of instruction gives her little opportunity to observe brilliance in him during personal interaction, although high ability is evident from his work, particularly from his innovative, non-standard, but usually valid, problem solving approaches. She particularly notices this in tests, for which she believes he never learns. His methods are often not economic, she remarks, and therefore he often runs out of time. She says that on the occasions that she does explain work to him, she has found that he sometimes shows less understanding and slower execution than she would have expected from him. She says that he has some philosophical misconceptions, such as the number line being circular, and she ascribes this to his intuition, based on private contemplation, not being challenged by access to the appropriate type and level of mathematics necessary to expose their fallacies. She says that André will frequently justify a statement by a simple remark that it is logical, yet he challenges things which she considers to be logical. She thinks this is because he does not generalise rules which are clearly applicable to a few cases without subjecting them to scrutiny. Therefore he needs to reason through concepts which many people would readily accept as common sense. This characteristic, together with communication limitations, sometimes make diagnosis of obstructions to understanding difficult, she says. She comments that while he is always faithful in his work, he "drags his feet" when doing sections that seem not to interest him.

André's Computer Studies teacher says that André prioritises according to his interest, and spends a good deal of his time at home working on topics he enjoys.

Consequently, André learnt to use four computer programming languages in a period of six months in 2002.

Extracurricular Activities

André plays in the school brass band, is a member of the school chess team and leads the school electronics club. For the past six years he has participated annually in the Expo for Young Scientists Competition, for the past three years in mathematics and science olympiads, for the past two years in the SAICE Schools' Bridge Building Competition and as part of the Kwa Zulu Natal team for the Interprovincial Amesa Maths Challenge, and in the past year in the KZN Mintek Quiz and the national computer olympiad. André misses school fairly frequently due to his involvement in these extracurricular activities and occasional day-visits to the University of Natal on invitation by lecturers who realise his potential.

4.3. Learning physical science

4.3.1. Introduction

André's learning of physical science is generally charged with interest, enthusiasm and mental activity. He will often voluntarily share new thoughts, ask questions, rigorously debate logic, playfully design variations, or bring the lesson to a temporary halt by switching off from the world in intense thought.

After introducing André's learning program, I describe a single physical science lesson, from which I identify some of the key characteristics of André's learning, which I then further describe and illustrate.

4.3.2. Learning program

In 2000 and 2001 I had formal contact with André for three hours a week during school time, during which I taught him physical science and biology. In 2002 I taught him physical science, biology and geography for five and a half hours a week. My approach makes it impossible to give a generalisation of how much time André spends learning physical science each week.

For the first two weeks of 2000, I attempted to follow a rigid, accelerated schedule. However, this could not accommodate André's inquiring nature and his slow initial, followed by rapid later, pace of learning. At times I have adopted a cross-disciplinary thematic approach, such as that summarised in Appendix H. Topics covered during this discussion on energy, when André was in grade eight, ranged from Newton's laws to radioactivity to photosynthesis and cloud formation. In four lessons between 4/4/00 and 8/4/00, for example, we discussed internal energy, adiabatic cooling, absolute and relative humidity, momentum, impulse, ticker tape problems, temperature and particle speed, synoptic charts, Coriolis force, trigonometry, s/t and v/t graphs, beats in sound interference, and the formulae for the speed of sound in string and in gas.

The topics André and I discussed in 2001 were determined by the grade 10 Physical Science syllabus, on which he was examined at the end of the year. However, relatively little time was spent on the grade 10 level of treatment of the work, as Table 4.1 indicates. Appendix I is a continuation of this table.

Table 4.1 Summary of four Physical Science lessons

Date	**Topic and lesson duration**	**Brief description**
31/01/01	Pendulums (1 ½ hours)	André showed how he had come to realise that pendulum frequency is determined by length to center of mass, rather than length. I introduced the circle representation. André was skeptical of it, but made use of it to try to derive a formula linking tangential velocity to pendulum position and length.
01/02/01	Wave graphs, Centrifugal force (1 hour)	I showed André a graphical representation of a longitudinal wave. He likened graphs of velocity and displacement of an oscillating point to graphs of V and I in a transformer. André pointed out that water waves were both transverse and longitudinal and asked about the energy locked in standing waves and what replenished energy lost due to friction. We discussed centrifugal force: pressure in a tyre when taking a corner and satellites in orbit.
02/02/01	Pendulum, Forces (1 hour)	André told me how he was proceeding with his pendulum formula derivation. We discussed centrifugal and centripetal forces and Newton's Laws.
06/02/01	Reflection and refraction (1 hour)	We went through reflection and refraction work from the grade 10 syllabus. André pondered on reflection from concave mirrors and wondered about the focal point's position and a threshold point beyond which reflection to the focal point does not occur.

4.3.3. A lesson on organic chemistry

André's first formal exposure to organic chemistry, on 12/04/02, is described below. The lesson is typical in the type of questions and comments made by André, but atypical in that he had little previous knowledge of the subject, he did not immerse himself in an extended period of private thought during this lesson, and he did not create a mental design to apply the knowledge gained in the lesson, as are frequently the case. The lesson was audio recorded and subsequently transcribed in its entirety. The following description was made by summarising my own perspective and the essence of the transcript.

My planned teaching approach was to go over a page of rules rapidly with André, after which I would ask him to apply these rules to the naming or formula-writing of a page of exercises. In my introduction I told him that the R on the rule page stood for a hydrocarbon chain. Half a sentence later he asked me what R stood for. I repeated my previous statement. He asked, "No. R". I repeated my answer. I then continued with my planned teaching approach. Two sentences on, he interrupted with a comment that the alkanes were themselves an R. A few similar interruptions occurred as I forged on with my planned teaching approach. About three minutes into the lesson he remarked, "But I don't know what the meaning of this is – so it doesn't help me listening to this … won't it just be easier to look at the example of this and then see…". I told him we would get to examples, but I wanted him to get an overview of the rules first so that he would know where to refer to them while making sense of the nomenclature.

Shortly after this, I asked him to derive a general formula for the alkanes. Short dialogue exchanges followed, mainly with him trying to find out what R was and what I wanted him to do, with suggestions of confusion and misunderstanding between us. About a minute later he abruptly produced a formula, which he then explained, checked and rearranged. I asked him to give me a general formula for the alkenes. He said he first wanted to see something, and drew a few chemical diagrams, asking about their names. After a while he remarked that R was always a chain with "how many ever hydrogen", and a little later he produced a general formula for the alkenes. I then asked for a formula for the alkynes. He wrote and muttered for a while, then drew structural formulae and made remarks or asked questions about them, such as:

> It's exactly identical except if it's taken... it's symmetrical... But how do you know, why must you take this one, um, this one – you know – and not rather that one? Because of the length of this chain. How would the naming be different if I added a C here... and H H H... then, um, I think I can see what the formula will be... is it 2x-2? (André, lesson transcript, 12/04/02)

For a while the lesson was steered by him drawing structural formulae for me or for himself to name, after which he gave generalising conclusions. He then turned to trying to think up cases where different names would be assigned to the same chemical. This led us to isomeric forms. He voluntarily worked on a general formula for determining the number of possible isomers for any given chemical formula, inserting three remarks about this abruptly in amongst the other discussions. The final one was rather unintelligible to me, but seemed to satisfy him sufficiently to end these comments:

> I realised now that I was wrong in saying that there's nothing you can't – it's only up to half of that. If there's only one whatever, that's joining, then it's only, then it's that, but if it's more than that you can have two and a seven, or something... (André, lesson transcript, 12/04/02)

During the lesson, we frequently questioned one another, misunderstood one another and, at least on my part, unintentionally implied incorrect meanings. It ended on a somewhat confusing note, as the following extracts show:

> André: Oh. But why's it obvious where the ane is?
>
> Teacher: Well, because each carbon can form four bonds and if there are no double bonds, then they're all uniform throughout.
>
> André: ur.... ur... But then you could just as well have named all the anes instead of all the ynes. One of these can be left out and they chose to do the anes -
>
> Teacher: No, but -
>
> André: Because if it's not an ane, if it's not an yne, then it's an ene - specify all the anes and ynes, then its obvious where the enes are. But they specify where all the enes and ynes are, then it's obvious where the anes are. They could just as well have specified the anes and enes -
>
> André: Or is that the varying factor within the group: the number of single bonds? Oh, so actually, this is a completely different thing to these two - it's the same but it's different according to this. This is a class that is a class, and that is the varying within a class - within each of these classes.

André: Or maybe just call... okay, maybe that is what it is, but having zero... is... zero.... Zero double bond, zero triple bonds, this one having... but then you mustn't associate this one with single bonds, because the number of single bonds doesn't...

(Extracts from lesson transcript, 12/04/02)

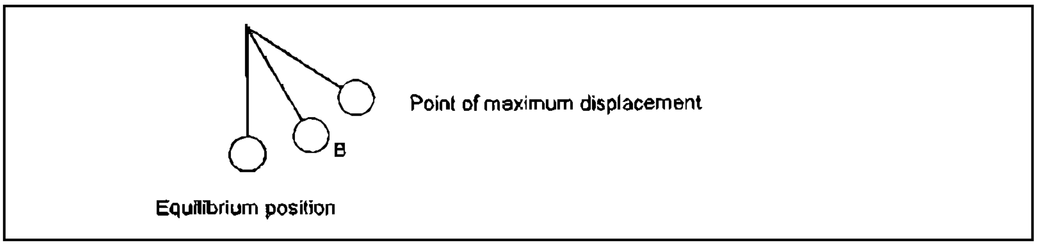
I identify six characteristics I have frequently observed concerning André's learning of physical science, most of which are illustrated in this lesson. André does not accept information superficially, he manipulates concepts while thinking deeply during learning, adds to and utilises a highly linked knowledge base, often organises information by reducing it through generalisation, extends his learning through applying knowledge to new contexts, and self-directs much of his learning of physical science. These will now be discussed in turn.

4.3.4. Key characteristics of André's physical science learning

Does not accept information superficially

As illustrated by remarks such as "But why's it obvious where the ane is?" and "They could just as well have specified the anes and enes" in the organic chemistry lesson, few explanations given to André are accepted without being challenged. He commonly dissects statements and instructions to determine their meaning, as he did when determining what R meant (p. 38), and he analyses them critically for inconsistency or illogicality, as illustrated by his remarks "this is a completely different thing to these two" and "then you mustn't associate this one with single bonds". He will generally interrupt dialogue to correct imprecision even if this is not central to the point the speaker is trying to convey. For example, more than once he has corrected the statement that acceleration due to gravity is 9,8m/s/s by qualifying that this only applies on earth (e.g. field notes, 08/05/01). He asks probing questions, is not satisfied with vague answers, is cautious of taking a generalisation too far and frequently exposes assumptions and sources of error and analyses these for significance. Some of these characteristics are illustrated in the extract below.

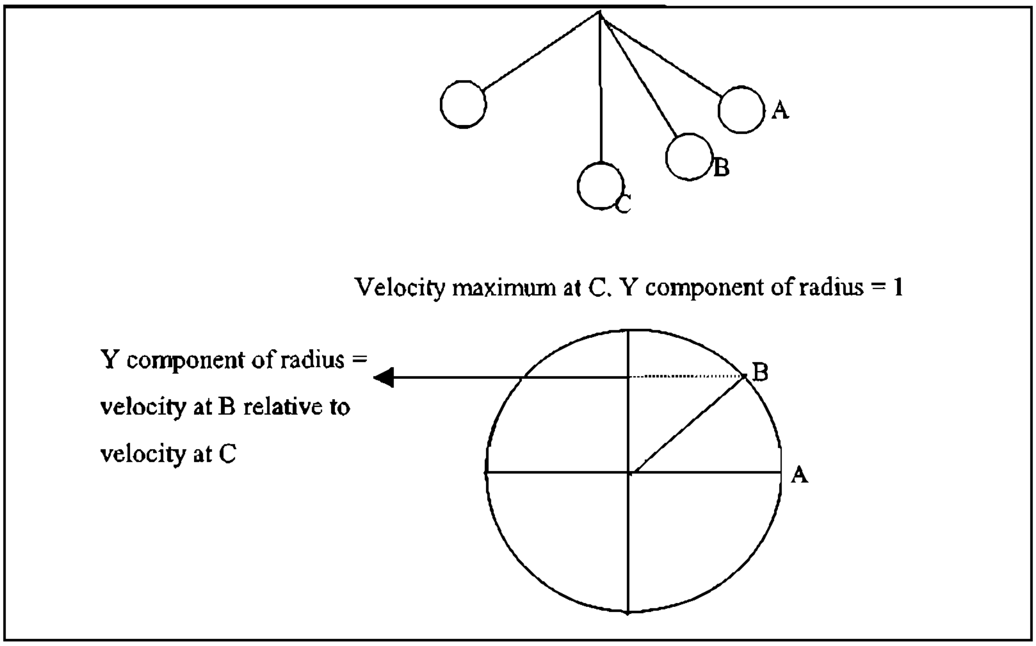
> The task was the calculation of the relative velocity of a pendulum at a point half way in distance between the points of maximum displacement and equilibrium, which we referred to as B, as shown below.



Three positions of a swinging pendulum.

He immediately realised the answer should be between 0,5 and 1 and that if one could work out the difference in height between A and B (h), then one could work out the change in potential energy from A to B, which would equal the kinetic energy at B, which could be used to find the speed. He then set about trying to find h.

He worked on this for a while. When it seemed to me that he thought he wasn't making progress, I told him that the tangential velocity of the pendulum bob can be represented in relation to its maximum velocity (i.e. at C) by the y-component of a radius rotating at a constant angular velocity, as shown below.

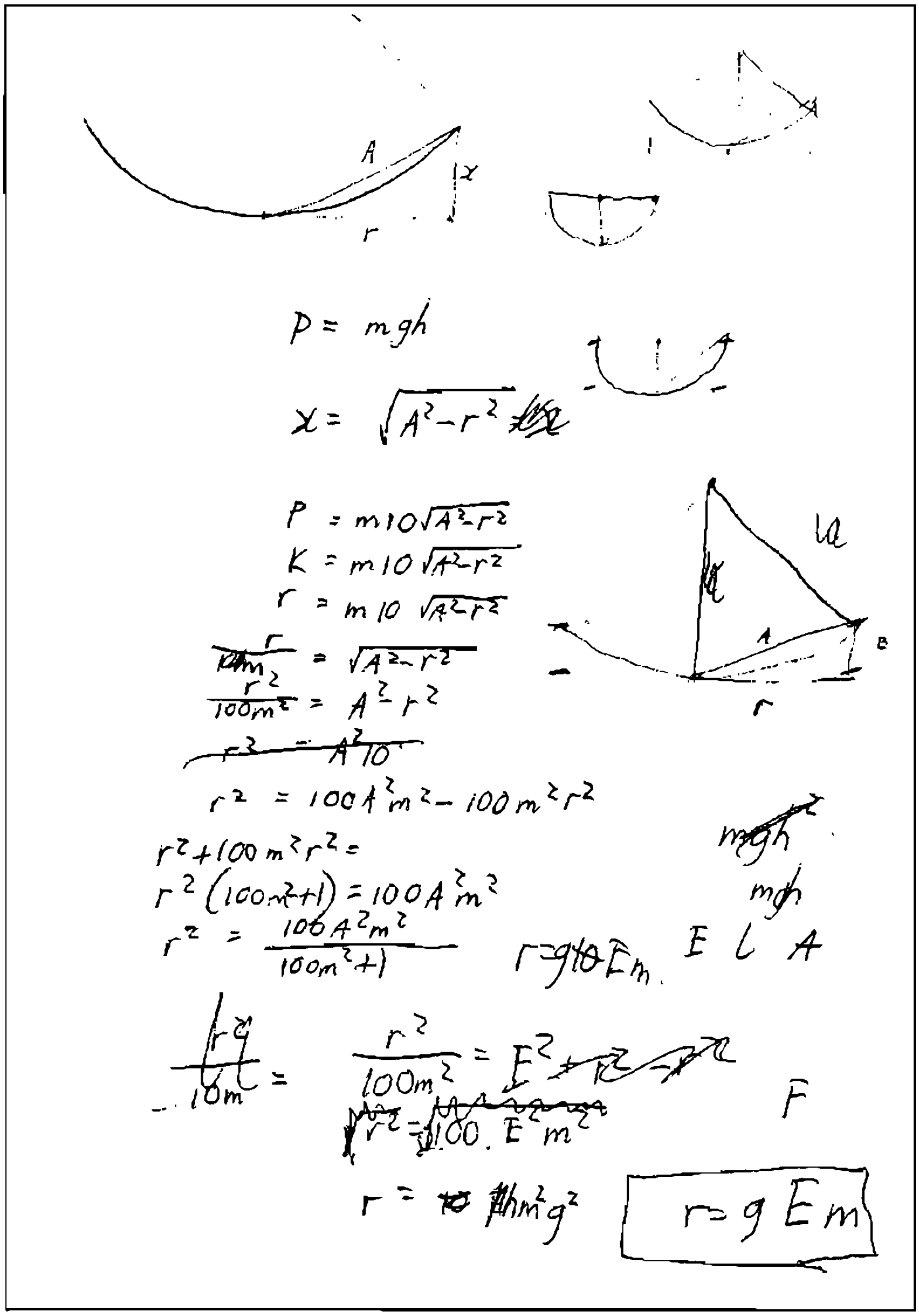


The circle representation for analysing the motion of a swinging pendulum.

He questioned this and spoke to himself of x and y components of g. After a while he agreed to assume this representation correct for the meantime, and, after two calculations (the first giving an unreasonable result), found an answer of 0,707.

I started to move on to something else, but he said he wanted to derive an equation linking T, L and g. He said that if the circle representation was correct, the circumference, 2 r, represented period, T. The y-component represented kinetic energy, so the radius represented energy (sum of kinetic and potential). He worked with this a while, and then said he would return to it when he could think straight.

Two days later he showed me his rough work, some of which is given below. He had derived equations for the potential and kinetic energies at any angle of the pendulum's swing in terms of its length, acceleration due to gravity and angle to the vertical maximum displacement.



$P = mgh$

$x = \sqrt{A^2-r^2}$

$P = m10\sqrt{A^2-r^2}$

$K = m10\sqrt{A^2-r^2}$

$r = m10\sqrt{A^2-r^2}$

$\frac{r}{\cancel{10m}} = \sqrt{A^2-r^2}$

$\frac{r^2}{100m^2} = A^2-r^2$

$\cancel{r^2 = A^2 10}$

$r^2 = 100A^2m^2 - 100m^2r^2$

$r^2+100m^2r^2 =$

$r^2(100m^2+1) = 100A^2m^2$

$r^2 = \frac{100A^2m^2}{100m^2+1}$

$r = g\cancel{10}Em$

E l A

$\cancel{mgh}$

mgh

$\frac{r}{10m} = \frac{r^2}{100m^2} = E^2$

$r^2 = 100.E^2m^2$

F

$r = \cancel{10}\,\cancel{h}m^2g^2$

$\boxed{r = gEm}$

A page of rough work produced voluntarily at home by André while thinking through the derivation of a formula.

> From this he had derived a formula for velocity at any instant and had checked this by substituting values into the formula. He found that the formula only gave velocity at B as 0,707 if angle of release were 90°, with accuracy (assuming the circle representation correct) of answer decreasing with a decrease in this angle. He was disappointed, but said he was still working on it.
>
> He pointed out the importance of not equating potential energy to kinetic energy when only the changes to them are equal. In his previous derivation it had been correct to equate change in potential energy from position of maximum height with kinetic energy at an instant, he said. However, in coming to a formula appropriate for all situations, he wanted separate equations for each, with the sum of the two being a constant for the motion. (Field notes, 31/01/01 and 01/02/01)

In the lessons described above, André did not superficially accept the circle representation for analysing pendulum motion. He first thought about its implications, as shown by his musings on x and y components of g, before he agreed to assume this representation valid for the meantime. After this he thought further about the representation's implications, linking, for example, 2 r to period and radius to energy. Also, he did not superficially accept the equation which he derived, the next to last paragraph describing some of the scrutiny he subjected it to while evaluating its limitations. Caution against inappropriate generalisation is indicated in the last paragraph, where he remarked about the importance of not equating potential energy to kinetic energy.

Manipulates concepts while thinking deeply

Questions and remarks such as "How would the naming be different if I added a C here… and H H H", and "I realised now that I was wrong", his drawing and alteration of structural formulae to test how these would influence naming, and his attempts to think of structures with ambiguous names, show that André was actively manipulating concepts while thinking about the work during the organic chemistry lesson. Nevertheless, the description on pages 38 to 40 does not do full justice to the depth of thought André employs as he learns physical science. He will frequently interrupt my lessons by falling into intense contemplation, punctuated by little mutterings to himself. Then he may briefly surface with a comment about being confused, or a question, or musings which send him into another bout of thought. After a while he may emerge with a remark that he "maybe understands", or he will give a generalising statement, or a "so then..." comment, or he may say that he will return to it when he can think clearly. As his father puts it:

> There is in him this ability to switch off - to a degree - from external interference. I believe he understands the business of thinking. Not many do. Further, he might not state the fact, but I believe he appreciates the rigour of his own logic and trusts it. (André's father, written comment, 19/04/02)

In the following extract, André reveals the value he places on thought in his learning:

> Normally understanding comes by a sudden revelation because you thought in the right way... After you get the revelation... something happens in your mind, so that after that you understand... Before the set of facts can lead you to understand it's got to be changed into a different format that can guide your thought process. (André, interview, 09/10/02)

Sometimes André will voluntarily, or on questioning, reveal some of his thinking. For example, he told me that momentum had acquired a precise quantitative meaning when I had shown him that force is the rate of change of momentum, and this is how he now recalls the equation F=ma:

> I think of a body that's decelerating because of a net force acting in the opposite direction to motion... and obviously it will lose momentum, and the rate at which - momentum is actually force stored - and the rate at which it loses momentum is equal to the force it exerts on the resisting. (André, interview, 29/01/02)

Thinking about a net force resisting a body's motion, in order to recall an equation for momentum, as André refers to in this extract, involves mental manipulation of the concepts of force and motion. Also, this and the other remarks reported above, illustrate that André thinks deeply while learning physical science

Adds to and utilises a highly linked knowledge base

André's remarks about momentum, given in the previous extract, together with the high degree of subsumption and linkage evident in his kinematics mind map (Appendix J), indicate possession of a highly linked understanding of dynamics. In contrast, André could draw on relatively little previously learnt knowledge during the organic chemistry lesson described on pages 38 to 40, due to very little prior exposure to the topic. Nevertheless, activities which linked sections of information are evident in this lesson, such as derivation of general formulae for three homologous series, and formulation of a rule to determine the number of possible isomers for any given chemical formula.

André told me (personal communication, 10/10/02) that he thinks understanding occurs when two or more isolated sections of one's stored knowledge become linked, and the further they had been apart from one another, the greater the revelation experienced on the formation of the link. Formation and use of links is illustrated below. The confusion at the start of the discussion is included to give perspective on the dialogical struggle which often accompanies André's learning in a classroom context.

> I explained Hendrik's motivation for saying that Archimedes' principle would not apply to a brick. André looked confused and asked me to repeat what I had said, which I did. I then set about explaining buoyancy. André seemed unable to take in what I said, causing confusion and frustration between us. He frequently asked me just to tell him the aim of the apparatus. I tried to do this by explaining what the apparatus demonstrates. He looked confused and repeatedly asked that I just give him the aim of the apparatus. Eventually he was satisfied and repeated that the aim was what he had wanted to know from the start. Then he restated some of what I had said and thought aloud about whether he agreed. He spoke about the meaning of the buoyant force and its relation to density. I commented that the buoyant force was caused by the difference in water pressure on the object's lower and upper surfaces. He related that to the volume of water which would have been there had it not been displaced. Then he spoke of floating objects and the force required to keep such an object submerged. He was clearly pleased. He commented on the water volume and density and density and force and then, clearly satisfied, said, "Yes - it must be so". (Field notes, 30/05/01)

In the last seven lines of this extract, André is shown to link the concepts of buoyant force, density, displacement, floating, force required for submergence, and volume. Together with the other examples given above, this shows that André adds to and utilises a highly linked knowledge base during physical science learning.

Organises by reducing through generalisation

The formulae André derived during the organic chemistry lesson, and remarks such as "Oh, so actually, this is a completely different thing to these two. This is a class that is a class, and that is the varying within a class - within each of these classes", show organisation of learnt material by forming generalisations. André frequently refers to the value of what he calls "elegance". For example, on 19/02/02, he informally remarked to me that if an elegant outcome can be reached, then it is worth working at something beyond the point of understanding or functionality. When asked what he means by elegance, he replied, "Explaining the most cases or the most observations, or thoughts, or whatever, in the least number of facts. Compressed data." (André, interview, 09/10/02). He said he thought this probably involved storing preferentially in the "understanding area" than in the "memorising area" of the brain and that a universal rule was more elegant than having to recall each instance. An example where André reduced a large amount of information into a single universal rule, is given below. The situation arose out of an inductive approach to calculus. I had given him data describing accelerated motion, and he was examining it for patterns.

> He pointed out that the difference between 12 and 3 was 9 (3x3), the difference between 27 and 12 was 15 (3x5), and between 48 and 27 was 21 (3x7). He then spoke about Fermat's last theorem and how he had been looking for a pattern the previous night. He explained that, for example, in the sequence x^2 there is always a successive odd number difference in the successive values:
>
> | | | | | | | | | | |
> |---|---|---|---|---|---|---|---|---|---|
> | x | 1 | | 2 | | 3 | | 4 | | 5 |
> | x^2 | 1 | | 4 | | 9 | | 16 | | 25 |
> | difference | | 3 | | 5 | | 7 | | 9 | |
>
> for x^3 there is also a pattern and surely there must be a pattern in the patterns. (Field notes, 8/05/01)

Later in the week, he voluntarily gave me the page of work in Figure 4.1 on page 47, to which the following refers:

> André showed me a pattern he had worked out the previous night. He had looked at the differences between consecutive numbers in n^x sequences where n is the counting number within the sequence, and x between sequences, and the differences of these differences, and the number of differences of differences until there is no difference between the differences. He discovered that the final difference (i.e. the value of the difference when all differences for that sequence are the same) = x! and the number of stages in differences is equal to x. He also pointed out how this fitted in with the calculus derivation pattern we were dealing with. (Field notes, 10/05/01)

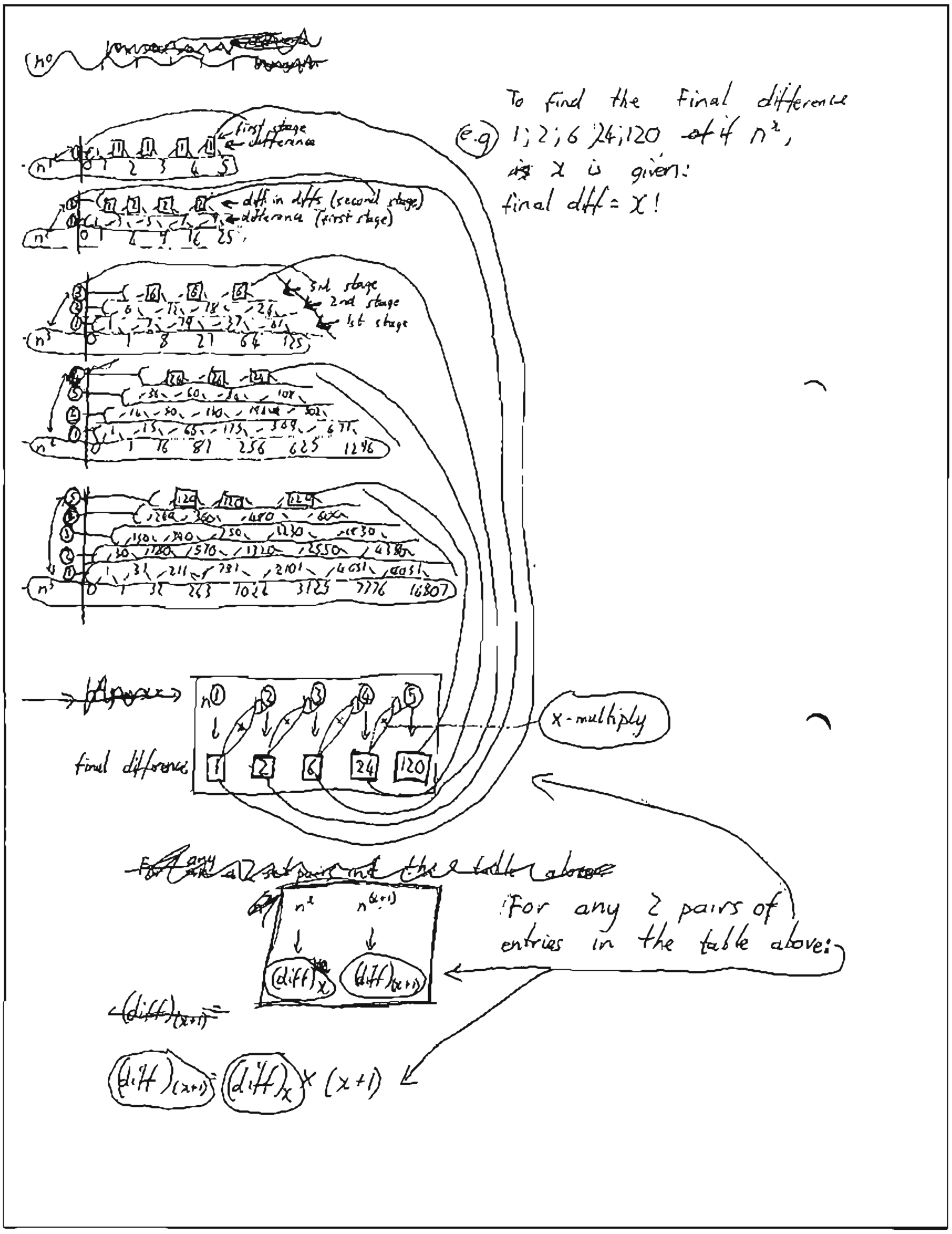


Figure 4.1 The differences of differences. Work produced voluntarily by André at home.

André's mind map of kinematics is given in Appendix J. It indicates his characteristic succinct style, as do his intense dislike for verbosity and preference for graphs, equations, schematic diagrams and lists, rather than verbal descriptions or paragraphs of writing. This is because, he says, the former are more elegant (interview, 09/10/02).

Extends learning through application

Although not demonstrated in the organic chemistry lesson, André will frequently redirect a lesson by telling me ways in which the topic under discussion may be applied. For example, after studying entropy, André spent most of the hour-long Physical Science lesson on 6/11/02 drawing and musing over a variety of nano-scale designs which might defy the law of entropy and generate electricity by extracting thermal energy from the surroundings. He also frequently interrupts my lessons by sharing designs he has thought up which appear to me to be only remotely related, or not related at all, to the topic under discussion. For example, during a discussion on metallic bonding on 28/10/02, he pondered about how one could make use of the scattered nucleons resulting from extraction of all the electrons from a substance, and on 30/10/02, while we were speaking about inorganic chemistry, he asked me whether I thought a centrifuge could be used as a pump and an air distiller.

Self-directs learning

As indicated in the third paragraph of the report on the organic chemistry lesson (p. 38), when I asked André for a formula for the alkenes, he remarked that he first wanted to see something, then drew a few chemical diagrams for himself or me to name, followed by generalising statements about nomenclature rules. Further, his interruptions about R, his decision to derive a formula for the possible number of isomers for any chemical formula, and the interrogation given in the dialogue extracts on page 39, beginning "But why's in obvious where the ane is?", illustrate André's frequent alteration of the planned course of my lessons by steering the dialogue along a path of his direction. This may be towards greater clarity of the topic under discussion, or may be about a different subject all together. He also often halts my progress with the request that he be allowed to think something through first, or by becoming so distracted by the topic he wants to explore that proceeding with my teaching is futile. Sometimes he will continue the thinking begun in class at home, and may share these reflections with me the next day, as he did for much of the lesson described in the following extract. My only input in this lesson was to supply the opening problem, which he solved only fifty minutes after the start of the lesson. For most of the lesson, I simply listened as André explained the statistical formula for describing entropy that he had learnt by reading a physics text the previous night, and as he mused over links between motion and relativity and units of measurement. The remarks André made about entropy had its roots in a lesson on the allotropes of sulphur (23/10/02). He had re-explained my description of the behaviour of sulphur on heating and cooling in terms of entropy and expressed confusion about what entropy meant. I referred him to relevant sections in a university physics text book, which he went through in his own time.

> He had been asked to find the answer to a routine grade 11 problem about gaseous pressure. He said he had been reading the information about entropy in gases which I had given him and had taken some time to understand the statistical formula for calculating the probability of any gaseous micro-state. He then set about explaining the formula to me. He said he thought that it was not inconceivable that all the particles would reverse their motion and the law of entropy would be defied. Also, he said that the same value for entropy had to be found for a particular gaseous state regardless of how the statistics were calculated since entropy is a state property, but this was not the case for the book's explanation.
>
> He then remarked that, since motion is relative, a train hitting a stationary car at 20km/h and a stationary train being hit by a car moving at 20km/h would have the same results, but on the other hand, the kinetic energies in the two situations are not the same. He said that since motion is relative one could view a person's motion relative to the universe rather as the universe's motion relative to the person, and since the whole universe has a huge mass, a huge amount of kinetic energy is somehow generated and somehow lost when a single person moves and then stops moving. He then tried to resolve these anomalies.
>
> Fifty minutes into the lesson, André returned to the grade 11 gas problem. The question asked for $500dm^3$ to be converted into m^3. André's think-aloud comments and his hand motions suggested he was visualising the sizes of a cubic meter and of a cubic decimeter to see how many $500dm^3$ volumes could fit into one cubic meter. He gave the correct answer. Then he drew a cubic millimeter and said there were a million of those in a liter. He exclaimed that a cubic millimeter was to a liter as a millimeter was to a kilometer. (Field notes, 25/10/02)

André was in control of this particular lesson for most of its duration. The extract demonstrates two aspects of self-direction in his learning, namely lesson redirection, and voluntary extracurricular learning. He veered from the gas problem I gave him to topics of entropy and relativity, which do not appear in school Physical Science syllabi, but which he came across through voluntary reading.

4.4. Conclusion

In this chapter I have presented information about André's background and learning environment, and have described André's behaviour while learning physical science, structured according to six frequently observed characteristics, namely: André does not accept information superficially, he manipulates concepts while thinking deeply during learning, adds to and utilises a highly linked knowledge base, often organises information by reducing it through generalisation, extends his learning through applying knowledge to new contexts, and self-directs much of his learning of physical science. These were illustrated through references to a lesson on organic chemistry, as well as other data excerpts. In the next chapter, I analyse and interpret André's learning within the theoretical framework outlined in Chapter Two, and guided by the study's research questions.

CHAPTER 5
INTERPRETATION AND ANALYSIS

5.1. Introduction

The purpose of this chapter is to answer the general question and associated sub-questions listed below, and to present evidence for these answers:

What are the characteristics of a high achiever's learning of physical science?

a) What strategies are used in the effective learning of physical science by a high achiever?
b) What roles do practical work and problem solving play?
c) What instructional strategies on the part of the teacher contribute to effective learning?
d) What intrinsic factors contribute to effective learning?

5.2. Learning strategies

Assertion 1: This high achiever uses a variety of learning strategies while learning physical science.

5.2.1. Introduction

Interpreting learning for understanding to mean undergoing conceptual change, I consider effective learning strategies to be those which:

- find new or accommodated forms of knowledge which may be acceptable for assimilation.
- evaluate whether accommodation is necessary before assimilation can occur.
- link assimilated knowledge elements.

This bears resemblance to Sternberg's (1987) classification of learning strategies as strategies of selective encoding, selective comparison, and selective combination. Using Sternberg's system as my starting point, but changing the headings to better describe what I observe in André's learning, I have chosen to group André's learning strategies under the headings: searching, analysing and linking, where these labels correspond, respectively, to each of the three learning processes given above. The organising structure I use in this discussion is given in table 5.1. I have observed a large number of manners of thought which André uses while learning, and have categorised these into five groups, which I have referred to as learning strategies. These are: probing, manipulating, reasoning, organising and applying. I use the term learning strategies to refer to observable patterns of behaviour which are controlled consciously or subconsciously by a learner, and which serve as tools for learning to occur. In addition, I have given more specific ways in which André behaves while employing each of these strategies, calling these learning tactics, in accordance with Schmeck's (1988) use of this term.

Table 5.1 André's learning strategies and tactics

Strategy category	**Purpose**	**Learning strategy**	**Learning tactic**
Searching	Obtaining relevant information for possible assimilation.	Probing	questioning identifying variables
Analysing	Evaluating whether accommodation is necessary.	Manipulating	performing thought experiments
		Reasoning	using proportion using rates using extremes using substitution using hypothetico-prediction using analogies
Linking	Linking assimilated knowledge elements.	Organising	searching for patterns deriving formulae determining hierarchy
		Applying	creating considering various perspectives

It is interesting to note that in Hobden's (2000) work, no identifiable strategies of the type noted here were utilised during problem solving by matric physical science pupils.

5.2.2. Searching

Probing

By probing strategies, I refer to activities used for obtaining information relevant for effective learning. During physical science lessons André uses questions to probe for relevant knowledge from information sources, and he may identify variables in order to decompose complex information, thus probing it for relevant sections.

Questioning. As described in Chapter Four, André has an inquiring nature. Therefore questioning is a commonly used tactic in his learning. Examples of questions André asked during the organic chemistry lesson described on pages 38 to 40 are: "Why must you take this one ... and not rather that one?", "How would the naming be different if I added a C here?", "Why's it obvious where the ane is?" "Is that the varying factor within the group: the number of single bonds?". In this manner he probed for information to enable construction of a coherent understanding of the rules of organic chemistry nomenclature.

Asking and answering questions is a form of dialogue, and it is through dialogue that communication gaps, resulting from individuals' perceived meanings not corresponding with one another, can be narrowed (Moodley, 2000), as illustrated in Figure 2.7 (p. 21).

André often finds answers to his questions through reading. For example, his understanding of the statistical formula for describing entropy resulted from voluntary reading induced by a question he had asked the previous day concerning entropy (p. 49).

Another source of information for answering his questions is himself. For example, after asking "why must you take this one... and not that one" he answered "because of the length of this chain". In the lesson described on page 49, he posed two questions about motion and relativity, and tried to answer them himself. This internal dialogue could be seen to be a search for information from prior-learning, or through logical reasoning, thus narrowing the communication gap existing between sections of his knowledge.

Identifying variables. When asked how he was able to form scientifically sound conceptions from information which causes most people to form misconceptions, André answered that he thought this had to do with mutually exclusive categorisation during concept formation so that conceptual overlaps which may cause inappropriate generalisations are eliminated (personal communication, 1/11/02). The example he gave to clarify this view was that, since motion is experienced in combination with friction, it is easy to generalise the every-day observation that applying a force is necessary for keeping a body moving, to the misconception that motion requires application of a net force. However, he had realised, at about age four (interview 29/01/02), that friction is not necessarily present during motion, and therefore conceptions of motion and friction should be separated from one another to prevent inappropriate generalisation. In other words, he had extracted relevant aspects from experience in a manner which allowed for scientifically sound generalisation. In this specific case he had done this by identifying the variables friction and motion. Similarly, in the extract below, he identified variables which may have affected his readings while practically determining the frequency of a pendulum.

> He explained why the mass and shape of the bob would affect accuracy and said that while counting more vibrations would decrease the proportion of error to reading time, it would also bring in more inaccuracy due to friction. He remarked that while observing the pendulum swing he could see that the amplitude was remaining very nearly constant, so friction with the pivot seemed to be very low. He said air resistance was a more significant factor than friction with the pivot and that inaccuracy in timing would be more likely to be significant than inaccuracy in length. He commented that a high amplitude would cause more air resistance, but if too low an initial amplitude were used it may become difficult to count the vibrations. He spoke about conservation of momentum and the effect of the pendulum's wobbling in directions other than the to and fro motion. (Field notes, 07/02/01)

These examples illustrate how André probes for information which is relevant for the formation of scientifically sound interpretations by decomposing a complex situation into its component variables.

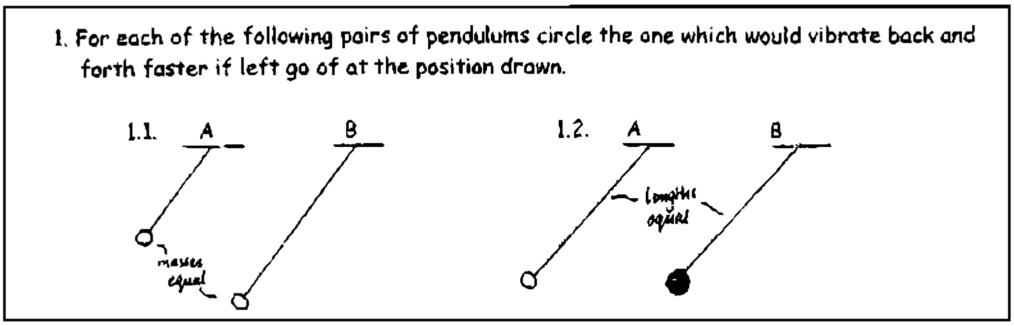
5.2.3. Analysing

By analysing strategies, I refer to activities used for critically evaluating information in order to determine whether accommodation is necessary for maintaining internal consistency despite the acceptance of new information or despite the rigorous re-examination of previously accepted information. This involves manipulating information and applying reasoning strategies to it, while comparing it with pre-existing knowledge.

Manipulating

André's concept manipulation while thinking deeply during physical science learning was described in Chapter Four. A tactic he uses to manipulate concepts is the performance of thought experiments.

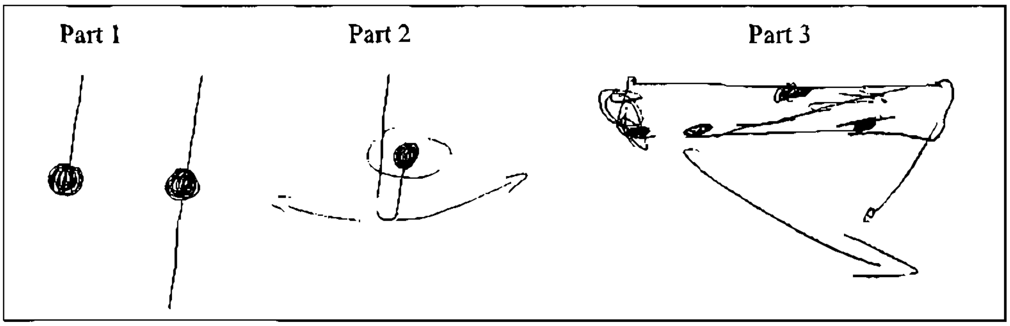
Performing thought experiments. André says that thought experiments, for example in outer space, have led him to form intuitive conceptions, e.g. to understand "the basics, like Newton's laws" before school-going age (interview, 28/03/02). An example of learning resulting from performance of thought experiments is described below.



1. For each of the following pairs of pendulums circle the one which would vibrate back and forth faster if left go of at the position drawn.

A Grade 10 Physical Science question given to André.

> He told me that while answering the questions given above, he had thought of two pendulums, which he drew, as shown in part 1 of the diagrams below. Although the second pendulum's length is significantly longer, he said, they would swing with the same frequency. Therefore the factor determining frequency is not length but length to center of mass. He then drew the diagram shown in part 2. He said that since the frequency would be determined by the length to the center of mass rather than the entire length, this meant that the force had to be transmitted all along the wire. This led him to speak of torque and angular inertia. He drew something, made adjustments, considered whether it would swing or not and made more adjustments, resulting in the diagram reproduced in part 3. (Field notes, 31/01/01)



Part 1 Part 2 Part 3

Pendulum diagrams André drew to explain his thoughts.

Performance of the thought experiment involving comparison of the two pendulums in part 1, above, led to disequilibration, which André resolved through accommodation (Dykstra, *et al.*, 1992) of his understanding of pendulum frequency in a manner that raised the precision ("not length, but length to center of mass"), therefore intelligibility, and therefore status, of his knowledge, resulting in conceptual change (Hewson, 1996; Hewson and Lemberger, 2001). Therefore, this example illustrates Gilbert and Reiner's (2000) view that thought experiments are useful for developing conceptual understanding.

Other examples, which have already been given in this text, which show André making use of thought experiments to manipulate concepts, include visualisation of resistance applied to a moving body for recall of Newton's equation of motion, comparison of the outcome of two collisions involving a car and a train, and consideration of the result of extraction of all the electrons from a substance.

Reasoning

By reasoning strategies I mean activities which enable the learner to draw conclusions from facts, and therefore, as Bruner (1971) puts it, go beyond the information given. I view a value of such activities as enabling the learner to make judgements about the implication of information, and therefore to determine whether accommodation is necessary. André uses various manners of reasoning. Those I identify are: reasoning using proportion, rates, extremes, substitution, hypothetico-prediction, and analogies.

Using proportion. The following extract suggests that André used his conceptual understanding of pressure, volume, molarity and temperature to deduce their proportional relationships to one another. It also describes how he checked the reasonability of the proportional relationships of pressure and volume to work using his understanding of these concepts. The latter was done with the purpose of determining whether information he had just become aware of, namely that PV had the same units as work, could be assimilated without need for accommodation. He found, through proportional reasoning, that this information was consistent with his existing understanding of these concepts.

> He derived a formula by reasoning through the proportional relationships of the variables involved (P,V,n and T), and remarked that he needed a proportionality constant. He exclaimed that PV had the same units as work. After a pause he said this made sense since a gas with a higher pressure for a certain volume was able to do more work than one with a lower pressure. Also, for a certain pressure, the greater the volume of the gas, the higher the ability of the particles to do work must be. (Field notes, 23/10/02)

This example is consistent with Fujimura's (2001) evidence for proportional reasoning being an effective strategy for facilitating conceptual understanding.

Using rates. In the extract below André reasoned using rates of change in order to determine whether observations he made in a practical investigation of refraction of light were consistent with his understanding of the concepts involved.

> I asked him to predict the next reading. He did so very rapidly by proportion, without writing anything or using a calculator. He then said this would be the answer if the angles of refraction and incidence were linearly related, but since they are not, the answer would be a little lower. As the data was collected, he showed great pleasure when his predictions and readings corresponded closely, and he continually checked back, determining the change of angle of refraction per change of angle of incidence, considering the reasonability of this, and using this information in his next prediction and in evaluation of measurement accuracy. (Field notes, 28/02/01)

On 10/05/02, André analysed a problem involving the effect of alteration of the angle of an applied force on motion by comparing the rates of change of sine and cosine relationships during angle increase.

In both of these examples, André made judgements about the reasonability of information as a result of deductions he made through referring to rates of change during his reasoning process.

Using extremes. During the organic chemistry lesson described on pages 38 to 40, André tried to think up structural formulae for which the nomenclature rules would be ambiguous. On 06/06/02, after I had spoken about air buoyancy, André reasoned that it could not be true that a pocket of air of any size that is warmer than its surroundings should rise, since a pocket of air so great that it comprised almost the entire atmosphere could never be buoyed up by the remaining air particles, and so for such a statement to be valid a pocket must be defined as having a volume ratio to its surroundings of 1 to infinity. On 05/03/01 he remarked that it was reasonable that the orientation for minimum deviation in refraction by a triangular prism should be such that light travels within the prism parallel to its base, since "there must be something special about the one position, out of infinite possibilities" where minimum deviation occurs (field notes). In these examples extreme cases were considered in order to draw conclusions about the acceptability of knowledge. This appears to correspond with

Howard's (1987) statement that the categorisation of borderline instances puts conceptual boundaries to the test, thus clarifying the rules of conceptualisation.

Using substitution. The following excerpt is taken from page 43. It illustrates André's use of substitution to evaluate the universality of a formula he had derived.

> From this he had derived a formula for velocity at any instant and had checked this by substituting values into the formula. He found that the formula only gave velocity at B as 0,707 if angle of release were 90°, with accuracy (assuming the circle representation correct) of answer decreasing with a decrease in this angle. (Field notes, 01/02/01)

Other examples of use of substitution in analysing information are his substitution of units for symbols to determine the meaning of R in the Universal Gas Equation, and to expose the relationship between PV and work (23/10/02), and substitution of values into Lorentz's formula to expose its physical implications (11/00). In all of these, deductions were made as a result of implications exposed by the act of substitution. In other words, André was analysing information by aiding his reasoning through substituting one type of information with another.

Using hypothetico-prediction. When undergoing hypothetico-predictive reasoning, learners make predictions based on their hypotheses, thus formulating ways to test the validity of their understanding (Lavoie, 1995). The extract given below illustrates André's use of this type of thought.

> In order to demonstrate that a flame covered with a jar dies as a result of increased presence of carbon dioxide rather than depletion of oxygen, André suggested that we cover one flame with a jar filled with oxygen, and one with a jar filled with air. He predicted that in the first case the flame would die more rapidly than in the second since the rate of combustion, and therefore carbon dioxide production, would be higher. However, when we did this practically, we found the flame covered with the jar filled with oxygen to burn for a longer time than that covered with a jar of air. André drew my attention to the motion of the smoke produced in the first case, and remarked that he thought the result was due to the stronger convection currents due to the greater heat produced by combustion in oxygen. He suggested that these were causing oxygen from below the candle's flame to rise, thus supporting combustion for a longer period than a simple collection of carbon dioxide from the top of the container downwards would have done. He proposed that this could be tested by comparing these results with those obtained when the significance of convection

> currents were reduced by using larger containers and longer candles. (Field notes, 22/02/01)

In this example André is shown to be drawing on his knowledge of the general principles of combustion and convection to analyse the specific case of a flame being extinguished when covered, through reasoning hypothetico-predictively between the general and the particular. Holland *et al.*, in Lavoie (1995), referring to the value of hypothetico-predictive reasoning in learning, state "The need for more accurate prediction favors the addition of further specialised rules, whereas the need for efficient prediction favors the addition of general rules to replace a large number of specialised rules." (p. 23). In the example given, a specialised rule André used to explain the negative outcome to his prediction, was that, for the small containers and candles used, convection currents prevented his prediction from being fulfilled. In this way he could still maintain his general concept of combustion without need for accommodation.

Lavoie (1995), in reference to hypothetico-predictive reasoning, says "This process of categorisation and recategorisation of knowledge leads to an expansion of knowledge" (p. 14). Expansion of knowledge, resulting from drawing specific formulae, predicting their names, and consequently formulating general rules about organic chemistry nomenclature, occurred during the organic chemistry lesson described on pages 38 to 40. This and the remarks "Or is that the varying factor within the group… Oh, so actually-" and "Or maybe just call… but then you mustn't associate this one with single bonds", show categorisation and recategorisation of knowledge by using the induction and deduction associated with hypothetico-predictive reasoning.

These examples and views seem to correspond to Moodley's (2000) reference to engagement with information on the notional level (Figure 2.4, p. 13), which includes hyper- (general) and micro- (specific) levels, and therefore hypothetico-predictive reasoning can be understood to contribute to effective learning through its continual interplay between the general and the particular. I believe that the discussion above shows that this is a valuable tactic in André's learning.

Using analogies. In the following extract André analysed an aspect of redox chemistry by comparing it to an aspect of electricity.

> He remarked that if there were two competing ions at an electrode, there should be a proportional reaction rather than one to the exclusion of the other. He likened the

> situation to two resistors in parallel, remarking that obviously one can't say that no current would flow in one simply because it has a higher resistance than the other. (Field notes, 30/10/01)

In this example André used an analogy as a communication aid and to formulate an hypothesis (i.e. a proportional reaction occurs when two ions compete for reaction) by deducing information about redox reactions which would be consistent with his understanding of electricity, and therefore would be acceptable for assimilation.

Another example of André's use of an analogy to reason his way to a deeper understanding, is his visualisation of a circuit containing an inductor, capacitor and alternating current source as a water system containing a flywheel, a compartment divided by an elastic partition, and two reservoirs. He said this had caused him to understand the voltage and current fluctuations in the electronic circuit as a result of thinking about the fluctuations in pressure and flow rate of the water in the analogous system (personal communication, 18/11/02).

These examples are consistent with the view given by Glynn, *et al.* (1995) that analogies are important conceptual tools in hypothesis generation, problem solution and explanation, and are influential both in thought, and actual, experiments.

5.2.4. Linking

As mentioned in Chapter Four, André possesses a highly linked knowledge base. I interpret his linking strategies to be those activities which form, alter, or strengthen links between knowledge that has already been understood, and that he does this by organising and applying his learning.

Organising

André's organisation of information through the reduction which results from generalisation, was described in Chapter Four. Tactics he uses to bring about this reduction are a search for patterns and derivation of formulae. Another tactic he uses for organising his knowledge is the determination of hierarchy.

Searching for patterns. Results of a pattern search activity are described on page 46, André's written summary of which is given on page 47. As a result of this pattern search, André reduced a large amount of information, namely the differences and differences of differences between consecutive numbers in the infinite number of possible n^x sequences, into two statements, namely that the final value of the difference when all differences for that sequence are the same = x! and the number of stages in differences is equal to x. The value of such a strategy to learning can be understood as reduction in cognitive load by freeing space in working memory (Lavoie, 1995; Lipman, 1991; Oberauer, 2001; Stevenson and Palmer, 1994).

Deriving formulae. André's derivation of a formula to describe the tangential velocity of a pendulum at various positions in its swing was mentioned on page 41, the rough work of which is shown on page 42. The purpose of this activity was to reduce and organise a large amount of information about the behaviour of an infinite number of possible pendulums into a single formula. However, André does not only derive formulae for the purpose of reducing information, as described above, but also to organise and reinforce organisation of concepts. This is demonstrated by his derivation of formulae from first principles even after the formula has been supplied to him. In early observations this was often done even when the formula was already in front of him. His think-aloud processes while deriving formulae in early data typically went like this: "The more the mass, the the more, the heavier, the less the acceleration. So these two are inversely so it must be... mass... I'm just quickly checking. Um. Yes, I think it's right." (André, lesson transcript, 07/03/01). When asked whether he always recalled equations from first principles, he replied, "Yes, that's normally how I recall most equations but it takes a bit long sometimes. Except Ohm's Law - I don't do that. Well, I used to, but I'm used to it, so..." (André, interview, 29/01/02). Ten months later, André said that he used memorised equations to a greater degree then than he had before because of repeated exposure to them, but he still considered it valuable to be able to derive formulae from first principles because:

> in an application you're not going to get: "here's this formula and now work that out". If you're working something out in a practical application, you need to work it out logically because it's not the same problem over and over. (André, interview, 09/10/02)

It appears, therefore, that André uses derivations to reason through a formula until he is comfortable with it and has used it a number of times, after which he uses the formula without needing to utilise this learning tactic.

Lavoie (1995) states that while routinisation of knowledge decreases cognitive load, it may do so at the expense of learner flexibility, which results from extensive internal and cross linkage between concepts. While derivation of a formula from first principles may be inefficient in terms of time, particularly when answering routine school exercises, André's comment, given above, suggests that it enables flexibility in problem solving. His use of this manner of reasoning while he is becoming familiar with the relationships expressed by the formula, suggests that during this period he is reinforcing conceptual links which will enable flexible thought. Routinisation follows once these links are firmly established, as indicated by his recall of formulae from memory after he has used them a number of times.

Determining hierarchy. In answer to a question of what strategies he uses when learning, all André could say was that determination of hierarchy was important, and questions were useful (interview, 28/03/02). His remark at the end of the organic chemistry lesson "that's a class, that's a class, that's the varying within a class" (p. 40) demonstrates hierarchical mental structuring. The value of this tactic to André's learning success is understood by the finding that expert problem solvers' success is related to heirarchical activation of knowledge (Gerace, 1992; Hauslein and Smith, 1995; Leonard *et al.*, 1996; Snyder, 2000; Willson, 1995).

Applying

André's extension of classroom learning by applying knowledge to new contexts was described in Chapter Four. In my experience, he particularly does this by creating his own designs and by considering situations from various perspectives. The value of this strategy to André's learning success can be understood by Woods' (1988) observation that knowledge becomes more meaningful when it is applied to specific situations.

Creating. As described in Chapter Four, André frequently applies what he has been learning through mentally creating his own designs. This is illustrated in the extract below, in which André's remarks following the practical observation of a voltaic cell, are given:

> He spoke of a set-up with various coloured ions which would successively be depleted, resulting in the production of various products and causing steps of LED brightness as the emf generated decreased, until the voltaic cell altered into an electrolytic cell requiring energy to cause a reaction. (Field notes, 30/10/01)

In this example, André applied his recently learnt knowledge of spontaneous redox reactions, as well as his prior knowledge of electricity and electrolysis, to a design of his creation, utilising and linking these concepts in the process.

Further examples, which have already been mentioned, of designs André created mentally during physical science lessons, are his nano-scale machines aimed at defying the law of entropy and generating electricity by extracting thermal energy from the surroundings, and of a pump and air distiller using a centrifuge.

I view the value of this tactic to effective learning as being the interest, and hence motivation, that application of general principles to specific situations generates (Woods, 1988), as well as the deep, notional, level of engagement with learnt material (Moodley, 2000) which must surely occur to enable application of the general to the specific in novel, creative ways.

Considering various perspectives. The excerpt below is taken from page 49. It describes André's consideration of situations of motion from the perspectives of energy and relativity.

> He then remarked that, since motion is relative, a train hitting a stationary car at 20km/h and a stationary train being hit by a car moving at 20km/h would have the same results, but on the other hand, the kinetic energies in the two situations are not the same. He said that since motion is relative one could view a person's motion relative to the universe rather as the universe's motion relative to the person, and since the whole universe has a huge mass, a huge amount of kinetic energy is somehow generated and somehow lost when a single person moves and then stops moving. He then tried to resolve these anomalies. (Field notes, 25/10/02)

Further examples of André's application of learning to new contexts through consideration of situations from various perspectives include his re-explanation of the fountain demonstration of the solubility of ammonia in terms of energy conservation (05/00), his re-explanation of the heating of sulphur in terms of entropy, which led him to question the meaning of entropy, which resulted in the learning described on page 49, his application of his differences of difference pattern to calculus, and his consideration of inertia and angular momentum while thinking about pendulums.

These examples demonstrate André's extension of learning through application of knowledge to contexts other than that in which it was originally learnt, an activity which promotes flexibility in learning (Lavoie, 1995; Willis, 1993).

5.3. Practical work and problem solving

Assertion 2: Inquiry, as typified by investigation and problem solving, is central to this high achiever's search for understanding.

It appears that André's learning through practical investigation and problem solving has largely been self-initiated and self-directed as a natural outcome of his inquiring nature, and that such activity began when he was very young. This is supported by his mother's and sisters' remarks, reported on page 31, which refer to self-posed problems and investigations tackled by André at a very young age. The six Science Expo projects André has produced to date have all been practical and problem solving in nature and were done voluntarily and with little assistance. André's remark that these projects have "taught me to accept problems as part of any undertaking" (André, written comment, 09/02), implies that he views problem solving as a normal component of learning.

As with the informal learning just referred to, André's formal learning of physical science indicates that problem solving is central to his learning, with many of his learning strategies being used in a context of solving problems posed by himself or an external source. During the organic chemistry lesson described on pages 38 to 40 he posed himself the problem of deriving a formula for describing the number of isomeric forms possible for a given structural formula. His voluntary formula derivation for the tangential velocity of a pendulum bob as a function of position, described on page 41, occurred in response to a problem I posed. This involved use of reasoning and organising strategies, as did the pattern search reported on page 46, which was the solution to his self-posed problem of finding a pattern for the differences of differences in consecutive numbers in n^x sequences. In the lesson described on page 49, André used an application strategy to pose problems for himself by considering situations from the perspectives of both relativity and energy. This revealed incomplete areas of his understanding which he consequently attempted to rectify. These examples indicate that problem posing and solving is central to André's physical science learning.

Examples of André's use of learning tactics in contexts of practical investigation include identification of the variables which may influence pendulum motion (p. 54), reasoning with proportion and rates during analysis of the results of a practical investigation into the refraction of light (p. 57), the hypothetico-predictive reasoning he applied to an investigation in which a flame is extinguished by being covered with a jar (p. 58), and analogy usage and design creation following practical demonstration of a voltaic cell (pp. 59 and 62). André told me, however, that he does not view practical work as having played a very large role in his formal learning, while it was very important in his informal learning (interview 28/03/02), but was less sure of this after reading the descriptions used in this dissertation. He did, however, still maintain that chemistry practicals do not contribute to learning because "they always come out wrong" (interview, 28/03/02). A situation is described below where limited learning occurred during André's attempts to make sense of unexpected results in a chemistry practical.

> André suggested that it was the hydroxyl ions from the sodium hydroxide rather than the water that were being hydrolysed. He wanted to use an ionic substance which would complete the circuit without undergoing a redox reaction during the investigation, and suggested sodium chloride. This yielded results which neither of us could explain. He commented that this needed further investigation since it may be something new. He decided to measure the resistance of the solution before electrolysis, first commenting that the Ohmmeter's battery may cause electrolysis. He found the resistance of the solution to be very high, but predicted that when electrolysis was in progress resistance would drop. He tested this prediction by measuring current strength and potential difference during electrolysis. He explained alterations over time as due to a decreased surface area of the electrode in contact with the solution as gas gathered, and due to bubbles clinging to the surface, then escaping from the electrode. He spent approximately an hour and a half exploring this situation, making various alterations to the set-up, but eventually abandoning a systematic approach and turning, instead, to playful mixing of chemicals to see what colours would result. (Field notes, 30/10/01)

Driver (1983) calls conceptual learning through practical discovery in science education a fallacy because observations are affected by preconceptions and skills of selection, which are influenced by prior knowledge and expectation. Further, the conversion of observations into perceptions involves interpretation, which is done using prior knowledge and imagination (Cobern, 1995). Therefore, André's failure to reach an understanding in the situation described above is not surprising. What is surprising, however, is that André seems to have been able to form scientifically sound intuitive conceptions about physics before school going age, largely, it appears, from self-initiated and self-directed practical and problem solving activities. André's use of a large variety of learning strategies, from a young age, particularly in contexts of practical investigation and problem solution, suggests to me that these strategies and these activities of inquiry are important components of his ability to form scientifically sound conceptions. I suggest that tied to, and inducing, his strategy usage and his disposition towards investigation and problem solving, are the characteristics of his deep learning style, described in Chapter Four, such as not accepting information at face value, manipulating concepts while thinking deeply, organising information by reducing it through generalisation, and self-directing learning, particularly by extending it, through application, to new contexts.

Therefore, I speculate that practical investigation and problem solving have been core ways in which André has been learning physical science from a very young age, and that these activities have led to effective learning because of his employment of a large number and variety of learning strategies and a deep learning style.

5.4. Teacher's instructional strategy

Assertion 3: ***Successful instructional strategy in the teaching of this high achieving learner involves allowing opportunities for extension by employing a largely learner-centered approach and utilising interesting open-ended tasks.***

5.4.1. Teacher flexibility during learner extension

Moodley (2000) says self-regulated learning occurs when a learner escapes from the pedagogical cycle propelled by extrinsic motivation provided by the teacher, to undergo learning propelled by the learner's intrinsic motivation, as shown in Figure 2.5 (p. 18). He identifies teacher prompting as a component which influences attainment of this autonomy in learning. Frequently André extends (i.e. self-regulates) his physical science learning without any external prompting. Prompts which are most successful in inducing extension in his learning are open-ended and learner-centered at least to a degree, but even closed-ended prompts may stimulate André to convert the task into an open ended problem if the teacher allows for a high degree of learner control. As, I believe, the discussion below shows, it is important for the teacher to have a flexible, largely learner-centered approach to instruction, to allow conversion of each of the three situational categories listed, into opportunities for effective learning. During this discussion, Lock's (1990) use of the terms open- and closed-ended, learner- and teacher-centered tasks, is utilised. Open-ended tasks allow for multiple solutions, designs, or answers, while the outcome of closed-ended tasks is decided before the work is undertaken. The degree of learner centeredness in a task is described by the degree of control the learner exerts in: defining the area of interest, stating the problem, doing the planning, deciding on the strategy for use, and interpreting the results.

No prompt. André's consideration of two sets of situations in terms of energy and relativity (p. 49), and all of his creative designs, were done without any teacher prompting. These self-assigned tasks were completely open-ended and learner-centered. In each case the role of the teacher was to provide time for André to think his self-initiated thoughts through by adopting a flexible, learner-centered approach to lesson direction and progression. In most cases, such as with the designs for extracting thermal energy from the surroundings by defying the law of entropy, a further role of the teacher was prior provision of the information which André then utilised during his learning extension.

Open-ended, largely learner centered, prompts. The lessons described and work reproduced on pages 40 to 43 began with the teacher-given task of determining the relative velocity of a pendulum at a particular position in its swing. This task may be described as open-ended in that André had never, to my knowledge, been given a similar problem, and had never been shown a particular solution for this kind of question, and therefore had to choose from a variety of possible solution approaches. Also, although I posed the problem with a specific answer in mind, which would class the problem as closed-ended, I was not sure whether this answer was correct. The initial task was teacher-centered in that I defined the area of interest and stated the problem, but was learner-centered in that André did the planning, decided on the strategy to be used (i.e. finding h so that he could find the change in potential energy between A and B, which would equal the kinetic energy at B), and began using it. However, when he appeared to reach a dead-end, I intervened by providing a strategy which I suggested he use (i.e. the circle representation for analysing pendulum behaviour), thus making the task more teacher directed. This intervention empowered André to find a solution and to extend his learning through using this representation in an attempt to derive a universal formula to describe pendulum motion. This self-posed task is open ended as multiple solutions are possible and an answer had not been decided before the outset of solution. While the general area of interest (pendulum motion) had been teacher determined, the statement of the problem, planning, decision of strategy usage and interpretation of results, were under André's control. Teacher flexibility was called for when André asked to be allowed rather to work on his self-posed task than that the lesson progress as planned. Given the interest and deep learner engagement, evident from André's voluntary persistence at the task, I think it is clear that this flexibility was worthwhile.

The differences of differences pattern search, reported on pages 46 to 47, is a further example of André extending a partially open-ended and learner-centered task (i.e. finding a pattern in a set of numbers) into a task which was almost completely open ended and learner centered (i.e. finding a universal rule for the differences of differences in n^x sequences).

A closed-ended prompt. The questions given at the beginning of the description of André's thought experiments concerning pendulums (p. 55), were closed-ended tasks in that they asked the learner to choose an answer from three options (A has a higher frequency, B has a higher frequency, or both A and B have equal frequencies). Nevertheless, they stimulated André to pose his own problems as the result of a critical evaluation of the answer which was obviously expected for question 1.2. By thinking that the larger bob had a shorter length to center of mass than the smaller bob, and therefore A and B may not swing with the same frequency, as one was expected to answer, he posed himself the problem of determining whether it was length or length to center of mass which determined pendulum frequency, and solved this problem by performing a thought experiment. He also mentally investigated factors affecting whether a pendulum will swing or not. In other words, the flaw in the closed-ended question stimulated self-directed learning as André posed open-ended problems for himself. Flexibility on the part of the teacher to accept and encourage this exactness and criticism, and to allow time for André to perform his thought experiments, enabled him to extend his learning beyond the relatively simple knowledge which the original question tested.

I conclude that the teacher's instructional flexibility, which results from a largely learner-centered approach to instruction, is an important factor in enabling André to convert various situations into opportunities for self-regulated extension in learning as he induces himself, or is induced through teacher prompting, to pose open-ended, learner-centered tasks for himself. In this way, one could say, the teacher utilises open-ended tasks which are teacher initiated as well as those which are learner-initiated. While André's learning extension is most commonly associated, in physical science lessons, with the original prompt, given by the teacher, being open-ended and learner-centered to a large extent, provision of examples where no teacher-given prompt resulted in self-regulated learning, and an example where a closed prompt induced learning extension, may suggest that the type of prompts the teacher provides has little influence on the effectiveness of André's learning. This, however, is not the case, as, I believe, the next part of this discussion shows.

5.4.2. Interesting tasks

André frequently refers to the importance of interest in learning, identifying it as the most important factor influencing his learning (interview 28/03/02). I identify four characteristics which determine whether André finds a task interesting or not. These are: novelty, meaningfulness, challenge and attainability. I now motivate this view by discussing each of these characteristics, in the context of André's learning, in turn.

Novelty. André says that a way for a teacher to kill intuitive interest is "if you've got to do lots of exercises... all with the same thing" (André, interview, 28/03/02). Other references to the importance of novelty in learning include his comment concerning a practical investigation: "but I didn't learn much because... I knew anyway what the results should be" (André, interview; 28/03/02), and the following comments:

> whatever experiments you do have to challenge completely different aspects of it. It's useless doing the experiment over and over with different data but still demonstrating the same thing... The more training cycles it goes through, the more established it becomes, but if the training cycles... don't correct anything, then it becomes wrongly established. (André, interview, 9/10/02)

> I think the most learning takes place when you come across something you can't explain and you change what's inside, and that actually trains your brain... There's this code and whenever there's data that it can explain, it gets reinforced and becomes more confident in your mind, but when there's a case that you can't explain, it's got to adapt to explain it, as well as what you can remember from previous cases. (André, interview, 09/10/02)

These statements correspond with a previous comment (interview, 29/01/02) that "things which cause amazement" make him think, since amazement is generally associated with encountering something which is new and unexpected.

Meaningfulness. The following extract illustrates that tasks which appear to André to be meaningless are met with resistance:

> When I asked André to provide a branching key for identification of reactants from observations for an inorganic chemistry practical we had done, he remarked that he could not see why one would do this as it would yield a less efficient representation than compilation of a simple list would since no rule could be derived from the sporadic data. (Field notes, 26/05/02)

As is discussed in the next section, I view André's learning to be driven by a belief system which values a high degree of precision, elegance, and transferability in knowledge. Consequently, I think that André gauges meaningfulness in tasks by considering their outcome in the light of these three characteristics. The task given above called for a less efficient, and therefore less elegant, outcome than a simple list would have, in André's opinion, and was therefore resisted. In contrast, the task of deriving a formula to describe pendulum motion had an elegant equation, which could be used in a large number of situations (i.e. was transferable to other contexts), as its outcome, and so, I interpret, was meaningful, and therefore interesting, to André. Similarly, the pendulum thought experiments described on page 55, had a more precise understanding of pendulum motion as their outcome, and so were interesting, and therefore meaningful, to André.

Challenge. André's remarks that the Science Expo has "taught me to accept problems as part of any undertaking" and "imposed an annual rhythm of creative activity on me without which I would have probably run to a boring halt" (André, written comment, 09/02), suggest that challenges (i.e. problems) keep André creative, active, and therefore interested. André's relish for solving challenging problems is illustrated by his comment that he wished I had allowed him to calculate that SALT would be able to detect light of the intensity of a candle on the moon, rather than telling him this (field notes; 18/04/02). The large amount of time he voluntarily spent trying to solve problems such as derivations of a general equation to describe pendulum motion and the differences of differences in n^x sequences, further indicate that he enjoys solving problems for which a solution is not readily apparent.

Attainability. André remarks that he thinks learning happens when the discrepant information is "on the forefront of one's knowledge" (André, interview, 09/10/02), which corresponds with Vygotsky's theory that optimal learning occurring in the zone of proximal development (Lee and Smagorinsky, 2000). To illustrate the importance of tasks being challenging while still attainable, i.e. being on the forefront of his knowledge, I contrast two of André's learning experiences. A lack of appropriate resources for making sense of results in the electrochemistry practical described on page 65 caused André to lose the interest which the initial observation incited in him ("it may be something new", lines 5 and 6) and therefore exchange careful systematic investigation for playful colour mixing after an hour and a half of relatively fruitless struggle. In contrast, my introduction of the circle representation for analysing pendulum behaviour, in the lesson described on pages 40 to 43, heightened André's interest in the task, as evidenced by his subsequent voluntary work, using this representation, which took him several hours. These two situations can be understood in the light of Figure 2.6 (p. 18), which is a graphical representation of the relationship of a learner's amount of invested mental energy (AIME) to the learner's perceived self efficacy (PSE) for performing the task. In the second situation, André clearly considered the task to be challenging, but, as a result of the information supplied, within his reach. In other words, PSE was optimal, and consequently the amount of mental energy he invested in the task was high. In the electrochemistry investigation, however, problem solution was out of André's reach due to resource limitations, i.e. he had a lower than optimal PSE and therefore invested less than optimal, although still considerable, mental energy in this task.

In conclusion, provision of interesting tasks is important for inducing effective learning in André, where interesting tasks are those which he perceives to be novel, challenging, meaningful, but attainable. Noting, as discussed in the previous section, that the kinds of tasks which he sets for himself are open-ended, and that tasks which are open-ended and learner-centered to a large extent, are particularly effective in inducing self-extension in his learning, it appears that this type of task is more likely to be interesting to André than closed-ended and teacher-directed tasks. This is supported by his remark that a teacher can kill learners' interest by making them do many exercises of the same type (interview, 28/03/02).

The success, in André's learning, of open-ended problems for which a solution is not readily apparent, and his remark that repetitive exercises kill his interest, are a clear contrast to Hobden's (1998) finding that South African physical science students expect the problem tasks they are given to solve at school to be well defined, familiar, and solvable within a relatively short time.

However, despite André's remarks about a dislike for repetitive exercises, he does sometimes make remarks concerning the value of revision, and there are a number of indications in the data, such as the account given below concerning learning of calculus, to show that repetition is also important for him to be able to recall and use learnt information in some situations.

> In a series on calculus and motion (field notes 8/05/01 to 16/05/01), André was rarely observed to apply the calculus derivation pattern, which the series taught inductively, during solution of problems. Instead, he reverted to approaches he was more familiar with (such as finding the turning point of a parabola using a method he had practised frequently in Kumon Maths), or which made more physical sense to him (by reasoning through the meaning of each variable and then logically finding the answer), even though use of calculus would have been more efficient. This series in Physical Science was complemented with work on calculus in his Mathematics lessons. He also wrote an examination on this section at the end of 2001. Nevertheless, when the topic was returned to on 21/09/02, he did not recall the derivation pattern, even when the original data used for induction was presented to him. However, once I had shown the pattern to him again and he had rephrased it, and given a few "so then" statements concerning it, he used calculus preferentially and rapidly in a largely formula-based, rather than logic-based, approach to answering motion questions during the next two days. (Summarised from field notes, 8/05/01 to 16/05/01and 21/09/02 to 22/09/02)

This extract describes how André reverted to use of well-practised procedures rather than using calculus until he had been exposed to it for quite a time, after which he used it preferentially for solving problems supplied for the purpose of practising its use.

The role of reinforcement through memorisation and exercising of conceptual and procedural knowledge in effective learning can be understood in the light of the reduction of cognitive load caused by routinisation (Lavoie, 1995; Stevenson and Palmer, 1994). On the other hand, emphasis on routinisation reduces learning flexibility (Lavoie, 1995) and may result in "deadening and banalisation" (Bruner, 1971, p.17) of knowledge.

In summary, I propose that, while reinforcement has its place in André's learning, novel, meaningful, challenging, but attainable tasks are important for maintaining his interest, and a teacher should nurture, manipulate, and provide freedom for self-perpetuation of this interest through providing necessary resources and through posing, and also allowing learner self-posing, of tasks which are open-ended and learner-centered to a large degree. In this way self-regulated extension may be induced in André's learning.

5.5. Intrinsic factors

Assertion 4: ***A belief system which values precision, elegance and transferability of knowledge drives this high achiever's effective learning of physical science.***

The alteration in André's learning behaviour after realising the aim of the Archimedes apparatus (p. 45) illustrates the pivotal nature of determination of purpose in his learning, as does his comment "if they didn't experiment wanting to actually find out how it works... then they didn't actually experiment" (André, interview; 28/03/02). I believe that learning is directed by learning purpose, as is illustrated by these two examples. This is consistent with Conceptual Change Theory which states that learners make decisions about conceptual alterations based on their evaluation of the status (i.e. intelligibility, plausiblity and fruitfulness) of competing conceptions, where a raise in conceptual status is the purpose of learning (Hewson and Lemberger, 2001). Bandura and Schunk, cited in McCombs (1988), refer to the roles of personal goals and standards, set by the learner, in directing learning and in generating interest and motivation. According to Schoenfeld's Framework (Schoenfeld, 1985), learners' belief systems determine their selection and use of resources, heuristics and control strategies. I identify a value for three characteristics, which appears to dominate André's physical science belief system. I interpret these as serving as criteria against which André evaluates a concept's intelligibility, plausiblity and fruitfulness, and as personal standards against which he evaluates his performance. These are a high degree of precision, elegance and transferability of knowledge. Therefore, I view the goal to which André directs his learning, and therefore the purpose of his learning, as being a raise in the precision, elegance and transferability of his knowledge. These are now each discussed in turn.

5.5.1. Precision

By a high level of knowledge precision I mean that conceptual boundaries and characteristics for conceptual abstraction are clearly defined and logically coherent, so that they can be applied in an exact, consistent manner.

To illustrate what I mean by the explanation given above, I refer to André's conceptualisation of the various organic homologous series as a result of engagement with the rules of organic chemistry nomenclature during the lesson described on pages 38 to 40. In this lesson, André inductively concluded general rules about organic chemistry nomenclature by determining the naming of structures he considered to be borderline instances (i.e. which he thought may have ambiguous names). In other words, he used extreme cases to clarify his understanding of the conceptual boundaries within the rules of nomenclature. He then tried to clarify general conceptualisation rules concerning the organic homologous series in a way that would coherently incorporate the specific rules of nomenclature he had been exposed to in the lesson, as the following remarks suggest: "But why's it obvious where the ane is?", "Or is that the varying factor within the group, the number of single bonds ... this is a completely different thing to these two ... This is a class, that is a class, and that is the varying within a class", and "maybe that's what it is, but having zero ... but then you mustn't associate this one with single bonds". In summary, I interpret this example as showing that André pays attention to precision during conceptualisation by trying to determine conceptual boundaries and criteria for abstraction unambiguously, and by trying to subsume these concepts within more general concepts in a coherent manner, thus forcing himself to further scrutinise criteria for conceptual abstraction and boundary formation, leading to more exact and consistent conceptualisation.

According to Figure 2.2 (p. 9), learners feel conceptually satisfied while they perceive concepts to fit together neatly like pieces in a jigsaw puzzle, but become disorientated when new information is presented which they perceive not to fit satisfactorily into their existing knowledge structures. In my opinion, from this it follows that the more stringent a learner's requirements for the fit between knowledge elements to be acceptable, the more likely it should be that discrepant information will challenge misconceptions. According to my interpretation, André's high regard for precision in knowledge causes him to set very stringent criteria for information to acceptably fit into his existing knowledge structure. Referring to the conceptual change he underwent as a result of the pendulum thought experiments described on page 55, for example, he described his initial view, i.e. a pendulum's length determines its period, to be "completely wrong" (interview, 09/10/10), since it is its length to its center of mass which determines its period. In contrast, I think the difference between these two statements would appear trivial to most children, who do not value precision highly (Stanton, 1990a).

André's comment that concepts must be mutually exclusive to prevent inappropriate generalisation (personal communication, 1/11/02), further support the view that he values conceptual precision very highly for ensuring scientifically sound learning. This statement has been expounded on, and the value of this view to his learning analysed, on page 54, and will not be repeated here.

Other examples which illustrate André's high value for information precision include his qualification that 9,8m/s/s is the acceleration due to gravity only on earth, his caution in evaluating and reducing sources of error in his pendulum investigation (p. 54), and his attention, in the following extract, in determining whether temperature or change in temperature, heat or change in heat, were referred to in an equation:

André:	but is it then change in temperature?
Teacher:	yes
André:	why?
Teacher:	because if you take its present state, how much heat must you add so its temperature will raise a certain amount?
André:	so the heat is the amount that you add not how much it has, so this should also be change in heat

(Lesson transcript, 09/03/01)

André's imprecision in the following comment, repeated here from the description of the organic chemistry lesson (p. 39), may be entirely due to communication limitations. However, contrasting it with most of André's quotations given in this dissertation, which demonstrate an ability for verbal clarity, I view it as possibly indicating André's recent emergence from the temporary confusion which appears to be a normal component of much of his learning, as is evident in his fairly frequent comments about not being able to think straight or being confused.

> I realised now that I was wrong in saying that there's nothing you can't – it's only up to half of that. If there's only one whatever, that's joining, then it's only, then it's

> that, but if it's more than that you can have two and a seven, or something... (André, lesson transcript, 12/04/02)

In contrast to the inexactness this extract suggests, André wrote a precise formula as an outcome of the remark given above. Therefore, I interpret a high degree of knowledge precision to be a purpose to which learning is directed, and therefore a desired outcome of learning, rather than a characteristic of André's knowledge and expression of that knowledge during the struggle and confusion often involved during knowledge construction.

In conclusion, I assert that André values precise outcomes to learning, where I take precision to refer to exactness and consistency in conceptual demarcation, and I believe that this contributes to scientifically sound conceptualisation by preventing inappropriate generalisations which may result from vague conceptual boundaries, and by sensitising him to information which is discrepant with misconceptions he may have.

5.5.2. Elegance

By elegance of knowledge I refer to simple, compressed order in the organisation of information. André defines information elegance as "explaining the most cases or the most observations, or thoughts, or whatever, in the least number of facts. Compressed data." (Interview, 09/10/02).

André says that if an elegant outcome can be reached, then it is worth working at something beyond the point of understanding or functionality (diary entry, 19/02/02). The brevity, due to a high level of abstraction and subsumption, of his kinematics mind map, given in Appendix J, indicates his high value for information elegance, as do his pattern searches and formula derivations, such as those given on pages 42 and 47. In contrast to the effort he was prepared to devote to these activities, the branching key I asked him to produce to summarise observations made in an inorganic chemistry practical, were met with resistance because this would "be less efficient than a simple list would", in other words, would be inelegant.

Viewing the mind's working memory as being of very limited capacity (Niaz and Logie, 1993), and link formation only to be possible between propositions which are simultaneously represented in working memory (Gagné, 1985; Oberauer, 2001), greater information elegance can be expected to result in lower cognitive load, despite representation of a larger amount of information in the working memory, and therefore an increased likelihood of beneficial link formation. André says that in order to understand something, one needs to see the whole in one's mind at once (personal communication, 1/11/02). However, for learning of complex information, this can only happen if information can be compressed, given the limited capacity of the working memory. This discussion corresponds to Bruner's (1971) view that effective learning must involve theory formation in order to avoid mental clutter, which is lethal in learning since very little knowledge can be dealt with at one time.

As in the case of precision, knowledge elegance appears to be an outcome of André's learning, and an internal standard which motivates him to manipulate information to a deeper level of understanding, or even beyond the point of understanding, rather than a characteristic of knowledge during the process of learning. In support of this view, I point to the inefficiency of André's derivation from first principles for formulae already supplied to him. Further, a relatively low degree of compaction and careful formulation of thoughts is evident in much of the rough work given on page 42, compared to the elegance of his differences pattern (p. 47). Even the relatively low degree of information compression in the first sentence of his explanation of the term elegance, compared to the second sentence ("explaining the most cases or the most observations, or thoughts, or whatever, in the least number of facts. Compressed data."), suggests that elegance in knowledge is attained only after some thought has been applied to it.

In conclusion, I assert that André values elegant outcomes to learning, where I take elegance to refer to simple, orderly data compaction, and I view the value of this characteristic to his learning as motivating activities which reduce the space that a given amount of information occupies when represented in working memory, thus reducing a major limiting factor in learning.

5.5.3. Transferability

By knowledge transferability, I refer to aspects of understanding which enable knowledge to be used in new contexts, i.e. which make knowledge utilisable, manipulable and flexible (Bruner, 1971; Gerace, 1992; Lavoie, 1995; Moodley, 2000; Schmeck, 1988; Willis, 1993).

Higher levels of knowledge abstraction, i.e. laws, principles, theories and abstract concepts, are more transferable than lower levels of abstraction, such as instances and concrete concepts (Howard, 1987; Stevenson and Palmer, 1994). This corresponds to Bruner's (1971) view of the importance of theory formation for enabling efficient learning of large amounts of information, and Moodley's (2000) reference to learning which leads to a deep understanding as involving engagement with the concepts, principles and laws of which the information forms a part.

The value of André's high regard for universality (interview, 09/10/02), and his use of learning strategies for effective conceptualisation, can be understood, in the light of the above, as aiding transferability of information to new contexts. André's value for being able to work something out rather than being limited to what has been learnt by repeated practise, in other words, his high regard for the ability to transfer knowledge to new contexts, is shown in the following extract:

> in an application you're not going to get: "here's this formula and now work that out". If you're working something out in a practical application, you need to work it out logically because it's not the same problem over and over. (André, interview, 09/10/02)

An example which illustrate André's high degree of abstraction and generalisation in learning, thus aiding information transfer, is his remark that the principle behind Lenz's law, which applies to electricity, is applicable to the atmospheric relationship between temperature and pressure, is the essence of LeChattelier's principle, and is a necessary consequence of the law of conservation of energy (field notes, 13/02/01). His quest for universal rules is illustrated by his formula derivations and pattern searches, and his scrutiny of the outcome of these for universal applicability, as shown, for example, in the case of his pendulum formula (p. 41). His use of probing, reasoning and organising strategies for conceptualisation is evident in the description of the organic chemistry lesson (pp. 38-40), for example by the generalising statements he made about nomenclature rules following his drawing and naming of structures of his own creation, and the critical evaluation of the consistency of his rules of conceptualisation in the dialogue extracts beginning "But why's it obvious where the ane is?" (p. 39).

Lavoie (1995) refers to multiple links between knowledge elements as ensuring flexibility and transferability of learning. Evidence of André's active linkage of information include his reference to momentum conservation, torque and angular inertia while thinking about pendulums (pp. 54 and 55), attempts to reconcile his understandings of energy and relativity (p. 49), and application of learning of entropy to mental creation of designs for extracting thermal energy from the surroundings.

From this discussion, I conclude that the effectiveness of André's physical science learning can partially be understood by the motivation that his regard for high levels of information abstraction, linkage and universality provide for use of learning strategies which facilitate transferability of knowledge, and that these enhance the flexibility and usability of his stored information.

5.6. Conclusion

In this chapter I have made the following assertions concerning the learning of physical science of this high achiever:

- The high achiever uses a variety of learning strategies while learning physical science.
- Inquiry, as typified by investigation and problem solving, is central to the high achiever's search for understanding.
- Successful instructional strategy in the teaching of the high achieving learner involves allowing opportunities for extension by employing a largely learner-centered approach and utilising interesting open-ended tasks.
- A belief system which values precision, elegance and transferability of knowledge drives the high achiever's effective learning of physical science.

In this chapter I have presented and supported my interpretation that André is motivated by interest and a high regard for knowledge precision, elegance, and transferability, and uses a large number and variety of learning strategies, particularly while solving open-ended problems and performing practical investigations, to learn physical science effectively. In the final chapter of this dissertation I look at possible implications of these findings.

CHAPTER 6

SUMMARY AND IMPLICATIONS FOR RESEARCH AND PRACTICE

6.1. Introduction

This is a case study of the learning of physical science of a high achiever, selected on the assumption, which is supported by literature, that instruction in learning strategies and styles used by successful learners may improve learning effectiveness of less successful learners.

Operating in an interpretive paradigm, qualitative data was gathered by participant observation aimed at sensing the complexities of the case (Merriam, 1988). The data corpus spans three years and is composed of audio-recorded lessons and interviews, field notes and written material. Data collection, analysis and interpretation were done in a reflective, inductive, cyclic manner, (Taber, 2000), guided by research questions about effective learning strategies used by the learner, effective instructional strategies used by the teacher, and the roles played by intrinsic factors, practical work and problem solving in contributing to effective learning of physical science by the high achiever. A rich, holistic description (Merriam, 1988) has been given in Chapter Four, to enable readers to form naturalistic generalisations of their own (Stake, 1994). This was followed, in Chapter Five, by my analysis and interpretation of the high achiever's learning success, using the theoretical framework outlined in Chapter Two, and guided by the research questions. A summary of the knowledge claims I have made in Chapter Five is given below, followed by comments on limitations to and implications of this study to further research and practice.

6.2. Summary of knowledge claims

In this study I have identified six frequently observed characteristics of this high achiever's learning, namely: he does not accept information superficially, he manipulates concepts while thinking deeply during learning, adds to and utilises a highly linked knowledge base, often organises information by reducing it through generalisation, extends his learning through applying knowledge to new contexts, and self-directs much of his learning of physical science. Additionally, I have made the following assertions:

- This high achiever uses a variety of learning strategies while learning physical science.
- Inquiry, as typified by investigation and problem solving, is central to this high achiever's search for understanding.
- Successful instructional strategy in the teaching of this high achieving learner involves allowing opportunities for extension by employing a largely learner-centered approach and utilising interesting open-ended tasks.
- A belief system which values precision, elegance and transferability of knowledge drives this high achiever's effective learning of physical science.

6.3. Limitations

André's individualised learning environment, together with his abnormal intelligence, reduces applicability to other cases, of knowledge gained from this study. A number of authors (e.g. Cicchelli, 1985; Gowan, *et al.*, 1979; Hauck, *et al.*, 1972; Kagan, *et al.*, 1988; Renzulli, 1979) say that teachers should expect more self-direction from gifted children than from more average pupils. To the extent that this is due to such children's superior mental processing abilities, which, according to Baron (1985) is the non-teachable component of intelligence, one cannot expect learning behaviour such as that described in this study, to develop in children of more average ability. Nevertheless, I believe that this work does give insight into the learning process, and suggests powerful manners of thought which may be useful, when employed by other learners, in raising effectiveness of learning of physical science.

6.4. Implications

According to Watts and Bentley (1984), school science education has traditionally neglected the personalisation of learning. Instead, science is portrayed as a "logically bound and internally coherent body of knowledge which the learner has to receive with no possibility of compromise or negotiation" (p. 309). Traditional teaching of science, they say, involves regurgitation of bodies of knowledge by teachers who dominate the class environment, limiting exploratory talk on the part of the learners. Few applications of science are provided and these are often contrived. This corresponds to research done in South African classrooms (for example Hobden, 2000; Ntshingila-Khosa, 1994). A comparison between the type of learning this encourages and the type of learning described in this study suggests that traditional teachers need to, as Watts and Bentley suggest, undergo a "rethink of what it means to be a learner, the personal commitment and involvement entailed in the act of learning" (p. 312).

This study supports the constructivist view that learning by understanding does not occur by mere transmission and acceptance of information, but rather that the learner needs to use active sense-making processes (Cobern, 1995; Leonard *et al.*, 2002; Wheatley, 1995). These involve an external dialogue between the learner and the information source and an internal dialogue within the learner as he/she evaluates the components of the new information in the light of prior learning (Gerace, 1992; Hauslein and Smith, 1995; Larkin, 1985; Novak and Gowin, 1984; Stevenson and Palmer, 1994; Willis, 1993). Even in the case of the highly intelligent learner under observation in this study, this is an effortful process which requires time, a degree of repetition, and mistakes and confusion along the way. This study shows that periods of self-regulated learning call for flexibility on the part of the teacher, allowing the learner some say in time and topic control and dialogue direction, accepting confusion and misunderstandings as necessary temporary features of productive learning, and accommodating learner reflection by providing pauses at appropriate places.

I have described a large number of learning tactics which the high achiever uses when learning physical science, and have categorised these into five learning strategies, namely searching, manipulating, reasoning, organising and applying strategies. It is possible that increased attention to such strategies in mainstream teaching could raise learner performance (Sternberg, 1987). However, it is important to note that these interact with other components, such as an extensive knowledge structure, well developed control and positive belief systems (Scheonfeld, 1985), and therefore may be of limited educational value if taught in isolation (Baron, 1985). Consequently, this study has sought to identify deeper characteristics which drive the intuitive use of these beneficial strategies. These were identified as an urge for greater precision, elegance and transferability of knowledge. These may be the scientifically beneficial components of intelligibility, plausibility and fruitfulness which are identified by Hewson (1996). They may also be the core values which drive a deep, reflective learning style for learning of physical science. The positive contribution of these self-posed standards to the high achiever's learning supports the view, taken by Bandura and Schunck, cited in McCombs (1988), that self-evaluation against internal standards allows learners to create self-incentives which, when fulfilled, result in satisfaction, which causes interest and an enhancement in self-efficacy. I suggest that it may be beneficial to direct further research towards finding practical ways to encourage learners to set internal goals for themselves, and, more specifically to this study, to cultivate a high value for precision, elegance and transferability of knowledge in learners. I suggest that teaching use of learning strategies, such as those identified in this study, may contribute towards this. However, contrasting the problem solving behaviour of the subject of this study, who uses a large variety of strategies while persisting at tasks for a long time, with the general behaviour of matric physical science learners, who use few or no strategies and expect problems to be solvable within a short time (Hobden, 1998; 2000), suggests that a more basic change in learners' outlook towards learning is necessary first. Learners need to realise that learning is a complex process which requires struggle, perseverance, and a variety of approaches, regardless of one's intelligence.

In addition to pointing to a need for learners to change their outlook on learning, this study suggests that teachers need to alter their views on teaching. One way in which it does this is by supporting other researchers' views that the traditional emphasis on highly predictable and repetitive exercises may discourage effective learning (Hobden, 2000). The subject of this study expresses a similar view to that voiced by some of the learners in Hobden's research, namely that these tend to discourage interest through their lack of novelty. The high achiever's view that the repetition characteristic of school exercises may reinforce less precise levels of understanding, and encourage dependence on memorisation rather than use of more universal, logical sense-making strategies, corresponds with statements (e.g. Hobden, 1998; Leonard, *et al.* 2002) that routine problems encourage unreflective behaviour since these tasks send the message to learners that physical science entails the application of formulae and algorithms without need for significant understanding of the subject matter. This study suggests that a flexible, largely learner-centered approach, with use of interesting tasks which are open-ended and learner-controlled to a large degree, may be effective in stimulating self-regulated learner extension.

In addition to the high achiever's individualised instruction, it is possible that his independent nature, together with use of strategies which are inefficient in a traditional school setting, such as recall of formulae through derivation from first principles rather than from memorisation, are responsible for his survival of the stint, a commonly observed phenomenon that gifted children suppress their precocity in an attempt to conform to normal standards of expectation (Bridges, 1980; Burden, 1979; Stanley, 1979; Watkinson, 1981). In the light of Bruner's (1971) remark, given below, that it is the dynamic complexity of thought which maintains interest in the learner, one wonders how many gifted learners' excellent thought (Lipman 1991) has been stifled by deadening and banalisation of knowledge through the traditional type of teaching described by Hobden (2000), Ntshingila-Khosa (1994), and Watts and Bentley (1984):

> The disciplines of learning represent not only codified knowledge but ways of thought, habits of mind, implicit assumptions, short cuts, and styles of humour that never achieve explicit statement... For these ways of thought keep knowledge lively, keep the knower sensitive to opportunity and anomaly. I draw attention to this matter, for studies in the history of knowledge suggest that deadening and banalisation are also characteristics of knowledge once it becomes codified. (Bruner, 1971, pp. 16-17)

Thus, André's appeal for novelty and challenge in learning may be the cry of other learners, particularly the more able ones, who could also be undergoing the exciting mental activity which "things which cause amazement" induce in him.

6.5. Conclusion

I suggest that this study shows that learning, even by the highly intelligent, requires time, perseverance, effort and the use of a large number and variety of strategies, and therefore does not occur by passive absorption. In other words, I suggest that this study stimulates a "rethink of what it means to be a learner, the personal commitment and involvement entailed in the act of learning" (Watts and Bentley, 1984, p. 312), and therefore supports calls for alteration of the traditional instructional approach where science is portrayed as a "logically bound and internally coherent body of knowledge which the learner has to receive with no possibility of compromise or negotiation" (Watts and Bentley, 1984, p. 309). Consequently, I believe it supports recent moves towards learner-centered transformation in South African education policy. This study suggests that physical science instruction should aim at teaching children how to learn through addressing their outlook on learning and introducing them to a variety of learning strategies, and it should aim at stimulating self-regulation in learning by providing learners with interesting, open-ended tasks. In other words, teaching needs to inspire learners and to equip them so that they can be inspired.

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APPENDICES

APPENDIX A SAMPLE: FIELD NOTES WITH INITIAL CODING.

Lesson Report 1

31/01/01
1 ½ hour
Periodic Motion

"Periodic Motion, Vibrations Waves Introduction" used as springboard. André had looked at it himself the previous night.

I asked him what the answer to Question 1.2. was. Superficially the answer is A and B have same frequency since mass has no effect on frequency. However, André pointed out that actually, since B is larger, its center of mass is lower, therefore the string is effectively longer and therefore the frequency is slower (v slightly, of course). Therefore he didn't know what to circle - an example of a question which disadvantages pupils who know more or understand more deeply.	compare : identify differences
He said as he read the a)-d) questions he thought of two pendulums, which he drew	manipulate
He reasoned as follows : although B's length is significantly longer, they would swing with the same frequency, therefore the issue is not length but length to center of mass.	predict, perform mind experime conclude
He then drew another pendulum	
He asked me whether this one's frequency would be determined by the entire length or by the length only to the center of mass, and then gave the answer to his own questions, saying it was obvious that the frequency would be determined by the length to the center of mass, and therefore that meant that the force had to be transmitted all along the wire.	question and answer manipulate
He then drew another pendulum while wondering whether it would swing with various arrangements. He spoke about torque, saying it shouldn't swing if equal forces are exerted at equal distances from the pivot. Then he commented that according to angular inertia they should swing. He concluded by saying he didn't think that they would swing.	describe from various angles Compare explanations
I then asked him to explain why each of the questions 1.1. to 1.3. were so (i.e. why only length from pivot to center of mass determines frequency). He did so very well.	
I then asked : If $v_{max} = 1$ what is the v at a point half way in distance between point of maximum displacement and equilibrium position?	
He immediately realised it should be between 0,5 and 1 and that if one could work out h then one could work out the change in potential energy from A to B which would equal the kinetic energy at B, which could be used to find the speed.	Planning of strategy before solving problem quantitatively : Predict range into which answer falls. Identify principle. Formulate steps of strategy.
He then set out about trying to find h.	

APPENDIX B SAMPLE: CODED TRANSCRIPT OF AUDIO RECORDED LESSON: 12/04/02.

169 Andre	but its not a complete formula, so then you add R to represent what ever else	3 *
172 Teacher	No, you're going to represent x - make x represent whatever	
173 A	Oh .. but why not make the digit R … because there … I don't mean …	
175 T	Well, then your formula's simple : just RCH3	
176 A	Yes	
176 T	Okay, some information you need before you can answer me : one thing is : how many bonds does carbon form : always?	
178 A	4	1
178 T	Correct. And this only has carbon and hydrogen and it never has any double bonds.	
178 A	… formula CH3 ….. I … really don't know … what else can it be then - there's one C and …	*
184 T	What's the simplest alkane?	
184 A	I mean CH3- or what ever	
187 T	Alright, what's the simplest alkane?	
187 A	um.. methane	1
187 T	Alright, because then R represents just H. What's the formula of methane?	
188 A	CH4	1
188 T	Okay	
189 A	Is this CH3 minus ….. alkane, just like that	3 *
191 T	No … no… no no. Methyl : that would be alkyl	
194 A	*I mean - yes - alkyl, whatever - this thing*	*
195 T	Its a group of compounds	
196 A	Oh, okay	
196 T	Which have only Carbon and hydrogen and no double bonds	
198 A	Oh, so the general formula would then maybe be … um … C 1 + x H 3 + y	2,5 !
202 T	Very funny!	
202 A	Why?	
203 T	C1+x what?	
203 A	C1 + okay, no, wait, whether I should only use xes. C 1+x y … um 2 … 1+ 2x + 1 so its 2+2x	2,5
209 T	Right, write it down for me - write it there, I've written a space for it	
212 A	Oh - but I'm not sure of it .. maybe I should just	◄
213 T	No - this is rough	
214 A	Its so nice - should keep it - file it and	
215 T	Ja, well, you'll learn from it …………………… that means you've got to speak louder	
219 A	What must I … so its 3 1 + what … say x H um 3 + 2x I which is C1+xH 4+2x … x is the number of carbon - I think, don't know, in the in the chain of atoms	2,5 ←
235 T	I'm just trying to check if that's right - I've got a simpler one - I'm just trying to see if this works … 1 + 1, 4 + … ya, I think you're right there. Now, I would just say Cx - or maybe, write it just so that its Cx	
242 A	CH - what again? If x is now 1 more than it was there … 3+2 … is that right - no, um … 2 ….. 2+2x	2,5
251 T	The way that I see it is that each carbon has to have 2 Hs, that's why it must be 2x and then the ends must each have another one,	
255 A	Oh	
255 T	so its 2x + 2. So you can write both or either of these two here (long pause)	
260 T	good. Alkenes. There's one double bond	
260 A	So the difference between these two was that this is : C is the number of carbon, I mean x is the number of carbons added, but here x is the number of - C - x is the number of carbons	5
265 T	yes	
265 A	mmmm… Alkenes - oh - general formula …. Um …. Just seeing something (writes)When it forms a double bond is it H ………………. H ……….so ……….(muttering while writing)So what do you call this? : Alkyl?	4,3

APPENDIX C SAMPLE: SORTING; 11/05/02.

What are the general characteristics of André's process of learning Science?

1. Strives for more concise and inclusive representation

AFFECTS INTRINSIC MOTIVATION

formula derivation such that universally applicable

2/2/01/01 : his equation only applicable when change in PE can be equated to change in KE, therefore not satisfied

likes most concise form of representation or explanation, therefore prefers graphs and equations to words, but when must use words, likes it when things are put in a unifying form

20/02/01 : graphs of displacement, acceleration and velocity and rate of change of acceleration, drawn on own initiative partially to try to make me understand something, and partially because he wanted a square graph, so wanted to see if any would be square.

6/03/01 : developed graph of image distance against object distance when asked to explain in words

28/02/01 : found + then used top (unrefracted) beam as reference rather than making markings (short-cut)

1/03/01 : pattern search for answering colour questions, formulation of general principles for finding answers in colour table exercise

5/03/01 : angle of deviation : comment that from infinite no. of possibilities, one would expect that the one which would cause min. deviation would have something special about it

13/03/01 : his theories about the number line, infinity and zero

22/03/01 : derivation of formula for convex lenses (his derivation included)

11/10/01 : his comment that he far prefers symbols to words

2. **Spends a large proportion of learning time on forming and accessing mental links and separations**

a) by making comparisons : AFFECTING AND AFFECTED BY **PERCEPTION**

i) through use of analogies

1/02/01 : s and v of graph of longitudinal wave compared to I and V of transformer graph

20/02/01 : commented on similarity of centripetal force equation and that for kinetic energy ("Kinetic energy per radius")

20/02/01 : acceleration of pendulum and of oscillating spring (note comment about preferring neatness of square graphs.. + found in electronics)

27/02/01 : wondered about link between optical density and density

27/02/01 : "sin is the function". "F-t graph proportional to a-t graph"

11/10/01 : "specific heat capacity is to heat capacity as volume is to density"

1/03/01 : "cyan and red sort of opposites or inverses since each needs the other to get white"

1/03/01 : reexplaining "minimum distance principle" from Conceptual Physics in terms of special relativity

22/03/01 comment : linking different units of pressure with one another

13/02 : cause-effect of atmospheric temperature and pressure: "tends to equalisation as in Lenz' Law"

ii) through proportional reasoning

28/02/01 : light prac

10/10/01 : played with numbers in table; ratio of l_f : c

29/09/01 : tried to solve by finding ratio of energy rise to specific heat capacity for each of the two substances

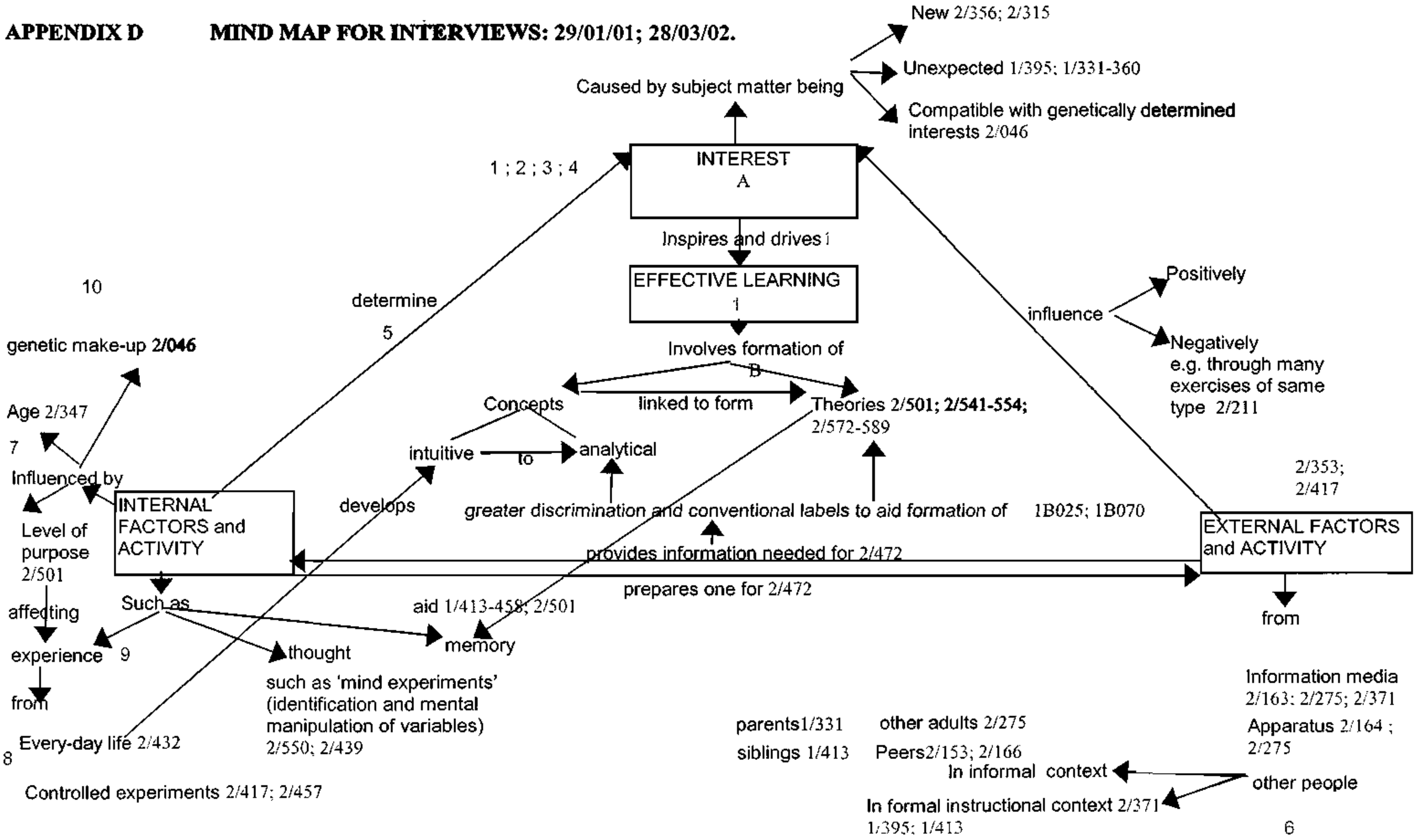
7/3/00 audio transcript F=ma (also see comment : 22/03/01)

20/02/01 centripetal acceleration

22/03/01 (Hooke's law) "force is directly proportional to the displacement and there's probably a proportionality constant"

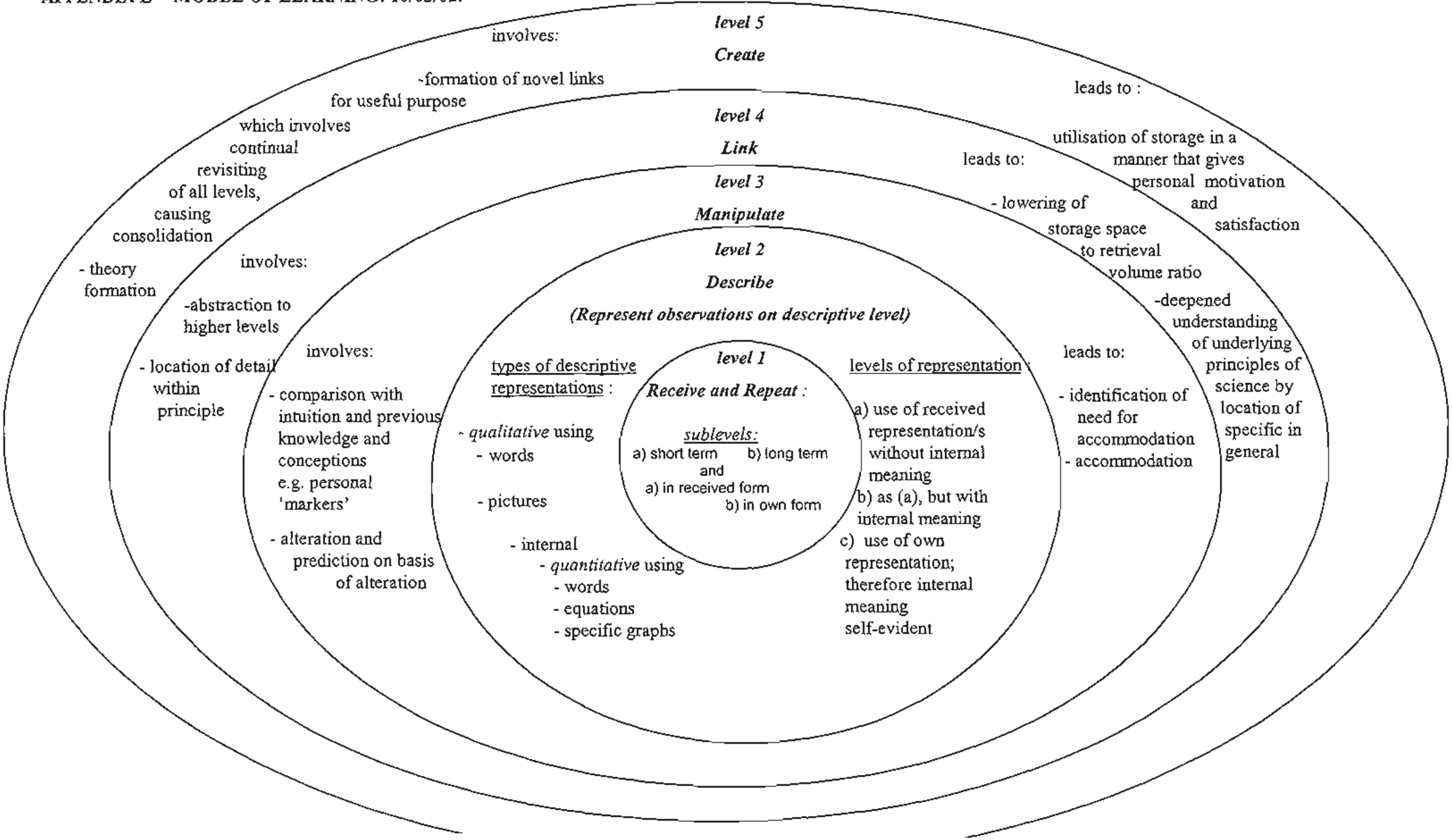
22/03/01 : "if g is increased ... if l is increased ... it must be frequency because f is inversely proportional to length"

APPENDIX D MIND MAP FOR INTERVIEWS: 29/01/01; 28/03/02.

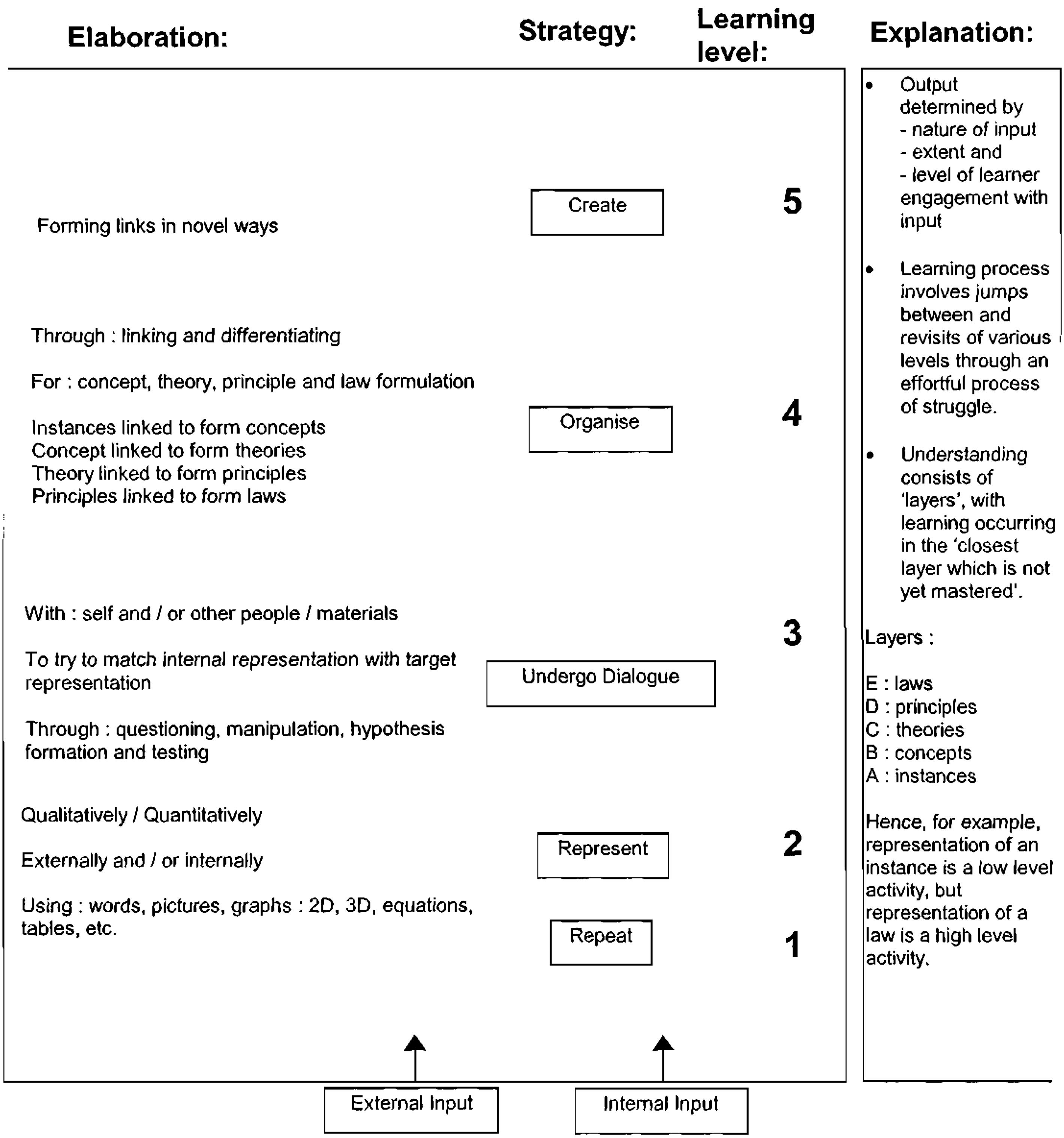


10 March 2002

APPENDIX E MODEL OF LEARNING: 10/03/02.



APPENDIX F LEARNING MODEL: 11/05/02.



Elaboration:	Strategy:	Learning level:
Forming links in novel ways	Create	5
Through : linking and differentiating For : concept, theory, principle and law formulation Instances linked to form concepts Concept linked to form theories Theory linked to form principles Principles linked to form laws	Organise	4
With : self and / or other people / materials To try to match internal representation with target representation Through : questioning, manipulation, hypothesis formation and testing	Undergo Dialogue	3
Qualitatively / Quantitatively Externally and / or internally Using : words, pictures, graphs : 2D, 3D, equations, tables, etc.	Represent	2
	Repeat	1

External Input

Internal Input

Explanation:

- Output determined by
  - nature of input
  - extent and
  - level of learner engagement with input
- Learning process involves jumps between and revisits of various levels through an effortful process of struggle.
- Understanding consists of 'layers', with learning occurring in the 'closest layer which is not yet mastered'.

Layers :

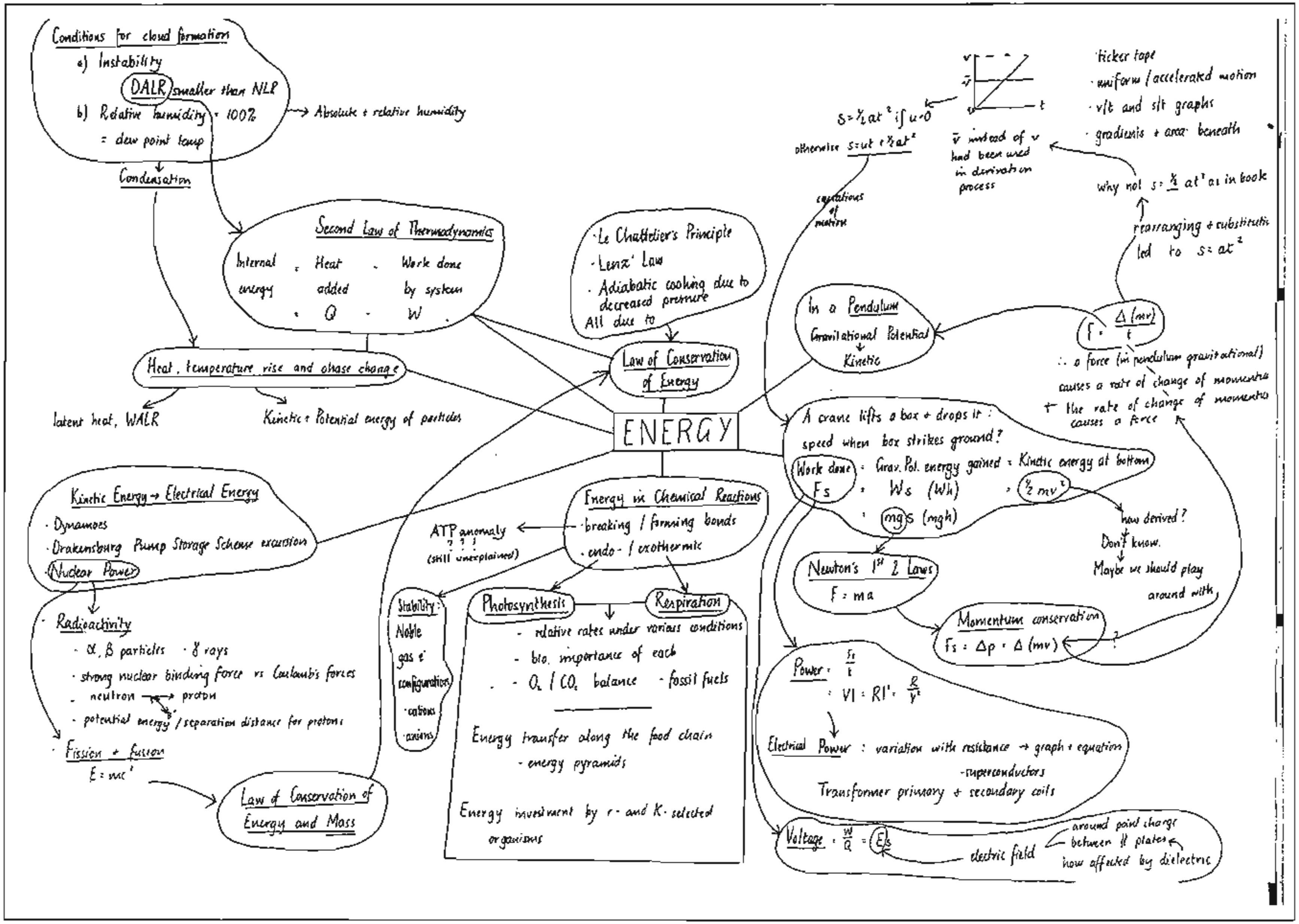
E : laws
D : principles
C : theories
B : concepts
A : instances

Hence, for example, representation of an instance is a low level activity, but representation of a law is a high level activity.

APPENDIX G ANDRÉ'S 2002 TIME TABLE.

Time	Monday	Tuesday	Wednesday	Thursday	Friday
8:00-8:30	Sci/Bio/Geog (work on own)	German (with class)	English (with class)	Sci/Bio/Geog (with Miss Stott)	German (with class)
8:30-9:00	Sci/Bio/Geog (work on own)	German (with class)	English (with class)	Sci/Bio/Geog (work on own)	German (with class)
9:00-9:30	Sci/Bio/Geog (work on own)	Sci/Bio/Geog (with Miss Stott)	German (with class)	Maths (work on own)	English (with class)
9:30-10:00	Sci/Bio/Geog (work on own)	Sci/Bio/Geog (with Miss Stott)	Sci/Bio/Geog (with Miss Stott)	Maths (work on own)	English (with class)
10:00-10:30	**Break**	**Break**	**Break**	**Break**	**Break**
10:30-11:00	Maths (work on own)	Sci/Bio/Geog (work on own)	Afrikaans (work on own)	Sci/Bio/Geog (with Miss Stott)	Sci/Bio/Geog (with Miss Stott)
11:00-11:30	German (with class)	Computer (with Mr P)	Afrikaans (work on own)	Sci/Bio/Geog (with Miss Stott)	Sci/Bio/Geog (with Miss Stott)
11:30-12:00	Computer (with Mr P)	Computer (with Mr P)	Sci/Bio/Geog (with Miss Stott)	German (with class)	Life Skills (with class)
12:00-12:30	Computer (with Mr P)	Computer (with Mr P)	Sci/Bio/Geog (with Miss Stott)	German (with class)	PT (with class)
12:30-12:45	**Break**	**Break**	**Break**	**Break**	**Break**
12:45-1:15	English (with class)	Maths (work on own)	Maths (with Mrs P)	English (with class)	Computer (with Mr P)
1:15-1:45	English (with class)	Maths (with Mrs P)	Maths (with Mrs P)	English (with class)	Computer (with Mr P)

APPENDIX H SCHEMATIC SUMMARY OF TOPICS DISCUSSED DURING THEMATIC LEARNING: ENERGY.



APPENDIX I SUMMARY OF ANDRÉ'S PHYSICAL SCIENCE LESSONS:

07/03/01 - 13/03/01.

07/02/01	Pendulum practical (1 ½ hour)	André measured the frequency of three pendulums of various lengths.
13/02/01	Pressure (1 hour)	1. We discussed atmospheric pressure and weather. 2. I made André prove each of the 5 statements in "Principles of Physics" (University text book) pg 184-186. 3. I made André derive the formula $P=\rho gh$ from first principles, and then to perform a practical demonstration of this formula using a manometer. 4. André determined the density of various substances using a manometer.
20/02/01	Centripetal force, acceleration. Hooke's Law. (1 hour)	I led André through the derivations of the formulae for centripetal acceleration and force, and Hooke's Law. We returned to the derivation of a formula for the frequency of a pendulum.
21/02/01	Waves worksheet (1 hour)	André answered a grade 10 exercise on wave calculations.
21/02/01	Centripetal acceleration equation, Aeroplanes (1hour)	We continued with the previous day's derivations. André investigated various designs of paper aeroplanes which I gave him to fold.
23/02/01	Refraction (½ hour)	I gave André grade 10 questions to answer. He pondered some aspects of the questions deeply.
27/02/01	Refraction equation derivation (1hour)	I led André through the derivation of the formula for refraction: $\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_1}{n_2}$
28/02/01	Light practical (1hour)	André practically determined critical angle, relationship between angles of incidence and refraction, and angle of deviation for triangular prism.
01/03/01	Refraction and colours (½ hour)	We went through the work in the grade 10 syllabus about refraction and colours. He likened minimum time explanation of refraction ("Conceptual Physics") to the theory of relativity.
05/03/01	Light summary (1 hour)	We went through a summary of the grade 10 work on light. He spoke about the minimum angle of deviation for a triangular prism.
06/03/01	Lenses (1 hour)	We discussed the alteration of image position and properties with object position. André summarised the lesson in a graph.
13/03/01	Magnification; Zero and infinity (1 hour)	We performed a practical investigation about magnification. André explained his ideas on zero and infinity to me.

APPENDIX J

ANDRÉ'S MIND MAP OF KINEMATICS.