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Conceptual representation of the Newtonian model of motion in university physics students

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CONCEPTUAL REPRESENTATION OF THE NEWTONIAN MODEL OF MOTION IN UNIVERSITY PHYSICS STUDENTS

An Abstract of a Dissertation

Submitted

In Partial Fulfillment

of the Requirements for the Degree of

Doctor of Education

Approved:

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ABSTRACT

The purpose of this study was to investigate how undergraduate students at the University of Northern Iowa who had taken prior coursework on non-calculus general physics with a unit on mechanics understand the Newtonian model of motion. In general, the study was concerned with reasoning strategies, the preconceptions that give rise to these strategies, and the schema that might be inferred from the preconceptions. In particular, the study focused on the three fundamental notions of the Newtonian model of motion: (a) that uniform straight line motion is equivalent to rest, (b) that motion is relative to an inertial frame of reference including that of the earth if the acceleration due to rotation of the latter is neglected, and (c) that uniform straight line motion can exist in the absence of a net force. Paper and pencil tasks in an interview mode were employed throughout the study. However, a short clinical interview was also used in order to assess prior knowledge of the above notions. The tasks were designed according to the Phenomenographic approach to investigating different understandings of reality, and the Rule Assessment Methodology in order for a variety of strategies, correct or incorrect, that a student might think of, be identified.

It was found that for the great majority of students uniform straight line motion is viewed as being fundamentally different from the state of rest, and that uniform straight

line motion can exist only in the presence of a net force. As for the notion of relativity, students adopt a "point of observation," rather than an inertial frame of reference, and motion is viewed relative to that point. This point was either on the ground or on the fixed stars depending upon the context of the problem in question. Several preconceptions and two types of schemata were also identified. In regard to the implications of the findings of the study for instructional practices, the explicit teaching of the Newtonian model as well as the provision of advance organizers and schemata at an early age should be given priority by physics instructors.

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CHAPTER I

THE RESEARCH PROBLEM

Introduction

Over the past two decades considerable international interest has been shown by science educators in studying children's as well as university students' ideas about physical phenomena, particularly those of mechanics. A wealth of both individual and group studies have been carried out, and there are a number of documents that review their findings (Connor, 1990; Driver, 1991; Driver & Erickson, 1983; Gilbert & Watts 1983; McDermott, 1984; Osborne & Freyberg, 1985). These studies were significant in that, for the first time, collectively they provided overwhelming evidence that students, at all levels of instruction, bring into the classroom a great many ideas about how the world works.

The research findings appear to indicate that, contrary to the behaviourist view of the mind as an "empty bottle" awaiting to be filled by the teacher, students are continually trying to make sense of the world by building models or schemata. These schemata are structures or clusters of prior concepts that students use in order to interpret any kind of new information (Carey, 1986; Resnick, 1983). They (schemata) are also subject to modification so that better predictions can be made in the future (Osborne, 1984; Pope & Keen, 1981). But they can remain unchanged so long as they make sense to the students, and provide them with satisfactory, although not correct, explanations and predictions (Dykstra, Boyle, & Monarch, 1992; Gilbert, Osborne, & Fensham, 1982; Viennot, 1979). Resnick (1983) points out that:

> All learning depends on prior knowledge. Learners try to link new information to what they already know in order to interpret the new material in terms of established schemata. This is why students interpret science demonstrations in terms of their naive theories and why they hold onto their naive theories for so long. (Resnick, 1983, p. 478)

Although any consideration about the origin of particular ideas is speculative, it seems that sensorimotor experience plays an important role in their acquisition. For example, through early experiences with lifting, pushing, throwing and catching objects, children do develop ideas about motion and forces, and the schemata "forces produce motion" and "the direction of force is the same as the direction of motion" are very common. Osborne (1984) calls these schemata "mini-theories" or "gut dynamics." He remarks that,

> through learning about the world, from the day we are born, we develop mini-theories which apply to specific situations and help us make predictions and decide on certain actions. The theories may operate at a subconscious level of thinking, they need not be articulated, and can be used in a spontaneous and intuitive way . . . the active efforts made at a young age to comprehend the world enable children to make predictions about what will happen, for example, to an object thrown from the high chair or kicked along the kitchen floor. . . . Gut dynamics is about the tangible world and influences motor skills and perception. This perception can be quite different from the reality staring one in the face. (Osborne, 1984, p. 505)

In addition, these schemata seem to be reinforced by everyday language and even by culture (Osborne, 1984; Solomon, 1987; Viennot, 1979). Newspapers, science fiction books, television, all have an influence on the way people acquire their vocabulary. The sport commentator quite often uses the expression "the ball was travelling with such a great force that"; and the popular expressions such as "the force of the explosion could be seen or heard," "your weight increases or decreases while you are going up or down on an elevator" together with "weightlessness" concepts of science fiction are widely used in everyday language. These expressions are what Osborne (1984) calls "lay dynamics," and they are expressions used to provide "entertaining conversations," although, as he points out, they are "of little practical use in terms of doing things" (p. 506).

Language, however, can have an effect on the understanding of fundamental concepts in another way. Mori, Kitagawa, and Tadang (1974a) investigated the role of language in understanding the concepts of time and space. They found that Thai children showed less tendency to judge the time duration of a moving object by the distance it moved when compared with Japanese children. This was attributed to the phonological distinctions between words showing temporal and spatial length. In Japanese, as in English, French, or Greek, both temporal and spatial length are expressed by the same word; in Thai these words are different. Similar findings regarding linguistic meaning are reported by Mori, Koyima, and Tadang (1976) who investigated the understanding of the concept of speed in Japanese and Thai children. It was found that the performance of Thai children was better than that of Japanese, and the researchers attributed this to the fact that in Japanese the concepts "early" and "speed" are expressed by the same word. And more recently, Choi and Bowerman (1991) studied the meaning of motion in English and Korean students. Through the investigation of the relative position of concepts, that is, the position in semantic space that one concept occupies relative to another, the different meanings for the concept of motion were noticed.

Cross-cultural studies carried out by Mori, Kitagawa, and Tadang (1974b) as well as by Ross and Sutton (1982) also show the effect of culture on the understanding of concepts. Mori et al. (1974b) studied the fundamental concept of time in Thai and Japanese children. It was found that, at the elementary level, Thai children opted for a circular concept of time (time returns to the same point), Christian Japanese opted for a segmental concept (time had a beginning and will end in the distant future), while public school Japanese children showed a rectilinear concept (no beginning or end). The same results were obtained from high school students. Although the segmental approach was discarded, Thai children opted again for a circular concept. Ross and Sutton (1982) found that it was the mother tongue, rather than the language used during school instruction, which determined the understanding of associated concepts such as "electricity" and "energy" among English children, Tiv speaking children educated in English, and Tiv speaking children educated in Tiv.

But to what extent should statements like "time returns to the same point," "forces are pushes and pulls," "forces produce and maintain motion," "gravity requires the presence of air," or "a car moves in a circle because the driver turns the wheel" be considered errors, partial understandings, or misunderstandings? And to what extent should they be considered inherited or acquired, and, therefore, culture and language determined? These questions are central to epistemology, but as yet no definite answers have been found.

Certainly, a distinction needs to be made, as has been pointed out by Driver and Easley (1978), between a misconception that results from an incorrect assimilation of scientific theories, and an autonomous alternative framework resulting from personal experience in an attempt to understand the world. The former is more likely to be held by secondary school and university students, whereas the latter seems to be common among children who have not yet experienced any, or adequate, instruction. However, this distinction is not very helpful. For when asked to explain what happens when a coin is tossed in the air, an answer like "we give the coin a force and it goes up until that force is all used up and then gravity takes over and the coin comes down" is very common among children (Driver, 1991) and university students alike (Clement, 1982). In fact, Clement found that 72% of engineering students at the end of a physics course failed to give the correct response!

Peters (1982) and Osborne (1984) also reconfirm that university physics students encounter conceptual difficulties. Osborne (1984) was surprised at the fact that, although 77% of a group of first year university students could cope with relatively complex applied mathematics, only 60% could correctly identify the force of gravity as the only force acting on a golf ball traveling through the air. The "force of the hit" that accompanies the ball throughout its flight was as common among Osborne's univerity students, as it was among a group of secondary school students (Watts & Zylbersztajn, 1981).

The consistency in the explanations of both young children and university students indicates that language and semantic knowledge cannot be the sole determinants of these mistaken ideas. In fact, the similarities between children who have been exposed to little or no instruction, and university students provide strong evidence for the existence of similar, or even identical, explanatory models, and tend to justify Johnson's (1987) position, namely, that almost all of our knowledge derives from bodily experiences through metaphorical projections into abstract domains.

Johnson (1987) remarks that behind each of our concepts there is a non-propositional mental model that guides our thinking process and understanding, and he provides a sound justification for the development of such mental models as constraints of our understanding. Drawing on the work of several researchers and philosophers, he argues that the most fundamental of all concepts is that of force, which, through bodily experiences from the day we are born, develops into various conceptual schemata such as those of compulsion, blockage, contact, attraction, balance, equilibrium, in-out orientation, containment, trajectory and so forth. Even emotions like anger are experienced through a conceptual schema involving a fluid within a container that can burst open, and our experience of symmetry is not in our perception of symmetrical objects, but, instead in our experience of bodily balance. In short, bodily motion and forces provide not only "a coherent meaningful structure to our physical experience at a preconceptual level" (p. 13), but also give meaning to all abstract concepts of our language through the use of metaphors. What is unfortunate though, is that these "abstract extensions" and "metaphorical elaborations constrain our meaning and understanding" (p. 137-138).

More often than not, students' models and ideas are different from the conceptions employed by the scientists, and have been referred to variously as schemata (Champagne, Gunstone, & Klopher, 1985), naive theories (Caramazza, McCloskey, & Green, 1981), naive notions (Reif & Larkin, 1991), children's science (Osborne, 1984), alternative conceptual frameworks (Carey, 1986), alternative conceptions (Dykstra et al., 1992), misconceptions (Helm, 1980; Savage & Williams, 1989), preconceptions (Clement, 1982) and so forth. However, it was Ausubel (1968) who first used the term "preconception" to describe these ideas. His claim was that these "preconceptions" are likely to persist despite instruction, and are therefore the most important factor in the learning process.

Although the terms schemata, preconceptions, misconceptions, alternative frameworks or conceptions are used interchangeably to describe ideas which are at variance with those of the scientists, it should be stressed that the the term "schema" refers either to a non-propositional mental image (Johnson, 1987) or to a structure that facilates conceptual organization (Anderson, 1985).
A "preconception," on the other hand, is better justifiable as a term to describe an idea or "preconcept" developed at an early age, even before formal instruction has begun, and which can remain unchanged unless challenged by the teacher. In addition, it is through the preconceptions of a student

that one can interpret his/her schematic structure, since access to, and interpretation of, the latter becomes possible only through the externalization of the former. And it is for this reason that research on conceptual understanding has concentrated upon preconceptions.

By now, a general consensus about these preconceptions has been reached with the following general characteristics:

1. They begin well before children encounter formal instruction, and they cross national boundaries (Driver, 1991).

2. They are often missed by the teachers (Anderson & Smith, 1985; Berg & Brower, 1991; Gilbert et al., 1982; Terry, Jones, & Hurford, 1985; Viennot, 1979; Watts & Zylbersztajn, 1981).

3. They can exist without any contradiction with what is taught by the teacher (di Sessa, 1982; Driver, 1991; Gilbert et al., 1982; Viennot, 1979).

4. They are change-resistant (Brown, 1989; Viennot, 1979).

5. They persist into adulthood despite many years of formal instruction (Driver, 1991), and can be held by university students (Clement, 1982; Halloun & Hestenes, 1985a, 1895b).

6. They are in many ways similar to the ideas held by the scientists of the past (Boeha, 1990; Halloun & Hestenes, 1985b; McCloskey, 1983; Whitaker, 1983).

7. They form a coherent theory that can explain phenomena of force and motion (Carey, 1986; Clement, 1982; McCloskey, 1983; Viennot, 1979).

8. They have less internal coherence than both the Aristotelian and the impetus theories of motion since they are not used with consistency in all contexts (Halloun & Hestenes, 1985b; McDermott, 1984; White, 1983).

9. They pose serious implications for the learning process (diSessa, 1983; Dykstra et al., 1992; Gilbert et al., 1982; Halloun & Hestenes, 1985a; McDermott, 1984; Reif & Larkin, 1991).

The last characteristic, namely the implications of the existence and persistence of preconceptions for the learning process, is the most important message that has emerged from the various studies on student conceptual undestanding. For unless these preconceptions are challenged by teachers, science will continue to be taught as a vocabulary lesson that will be nothing more than "a recipe for disaster" (Carey, 1986, p. 1,124). And as Viennot (1979) has put it, preconceptions, particularly about motion and forces, will result in juxtaposition of academic knowledge and intuitive science, "laying one on the other without conflict between the two" (p. 213).

Purpose of the Study

The purpose of the present study was to investigate how undergraduate students who have taken coursework on non-calculus physics with elements of Newtonian mechanics understand the concept of uniform straight line motion, that is motion with constant speed in a straight line, as well as the notion that motion, in general, is relative to a frame of reference including that of the earth.

In particular, the study was concerned with reasoning strategies, the preconceptions that give rise to these strategies, and the schema that might be inferred from these preconceptions. The ultimate purpose of the study, however, was to contribute to an improvement of the teaching and learning of physics in terms of efficiency and effectiveness.

Research Questions

1. Do students have the qualitative definition of uniform straight line motion?

   a. Do they view uniform straight line motion as being a relative kind of motion?

   b. Do they view uniform straight line motion as being equivalent to rest?

2. Do students view motion, in general, as being relative to a frame of reference, including that of the earth if its acceleration due to rotation is considered negligible?

3. Do students have the conceptual link between uniform straight line motion and zero net force?

4. What strategies do students employ in their reasoning process?

5. What preconceptions lead students to employ those strategies?

6. What schema might be inferred from those preconceptions?

7. What interpetation might be given to the representation of the concepts of force and motion?

Significance of the Study

Undoubtedly, any study on conceptual understanding will uncover a number of preconceptions, and, at the same time, help the researcher with an interpretation of the students' conceptual schema. As previous research in this area has shown, these schemata and preconceptions are the single most important factor in understanding any new piece of knowledge (Dykstra et al., 1992; Carey, 1986; Resnick, 1983).

Conceptual schemata become manifest in reading (Anderson, 1984), human reasoning (Johnson, 1987; Johnson-Laird, 1983), problem solving (Chi, Feltovich, & Glaser, 1982; Greeno, 1978; Larkin, 1983; Larkin & Reif, 1979) and science learning (Carey, 1986; Driver, 1991). However, more often than not, conceptual schemata, particularly in the area of force and motion, give rise to preconceptions that interfere with formal instruction. Viennot (1979) remarks:

> We all share a common explanatory scheme of intuitive physics which, although we were not taught it at school, represents a common and self-consistent stock of concepts and which, however wrong it may be, resists attempts to change or modify it. This intuitive physics presents, at the very least, a considerable challenge to teaching. (Viennot, 1979, p. 205)

Current views in science education (Basili & Sanford, 1991; Brown & Clement, 1989; Carey, 1986; Dykstra et al., 1992; Gorsky & Finegold, 1992; Posner, Strike, Hewson, & Gertzog, 1982; Resnick, 1983; Shuell, 1987) hold conceptual change as the number one priority of science teachers. This, in turn, implies that teachers first become aware of what preconceptions and schemata the students might have, and then challenge them in order for a conceptual change to be produced. Gilbert, Osborne, and Fensham (1982) did in fact find that the teacher's explanation is not enough, since the problem seems to be not the acquisition of the new concept, but the reluctance on the part of the student to give up the initial preconception. In most cases students adopt either two perspectives or a mixed outcome. In the first case students retain both the original conception and the teacher's explanation as a memorized version, whereas in the second case they can learn some of the taught material but fail to integrate it into their conceptual framework.

Similar findings have been reported by Halloun and Hestenes (1985a); instruction brought about only a 14% improvement on student knowledge. As they report, the same preconceptions were entertained even after the completion of the instruction. Halloun and Hestenes (1985a) also found that physics students could successfully solve problems without understanding the underlying conceptions, thus confirming what both Chi, Feltovich, and Glaser (1982), and Larkin (1983) reported from their own studies.

However, unlike previous studies which investigated isolated concepts in specific contexts, this study attempted to assess the "whole picture" of the Newtonian concept of motion in the students' cognitive structure through a wide variety of problem situations. For "only by keeping careful track of how students respond in a rich variety of situations will we be able to better infer which conceptions are responsible for their behavior" (Dykstra et al., 1992, p. 621). It was thought that this approach would enable students to put into relationship all their prior conceptions and thus present a more coherent picture of how they understand. Previous research in the area of Newtonian mechanics has concentrated mainly on the motion-implies-a-force preconception. The present study attempted to assess all related concepts that might have been in the students' schema of motion.

But there is also another reason why this study was important. The concept of motion is the most fundamental of all concepts, since it is central to all of physics. There is an argument, that in order to understand physics one has to understand mechanics. It is therefore imperative that a good understanding be secured before students move on to other areas of physics. How can students be taught even an introductory special relativity course without a good understanding of the concept of motion? Even collisions of high-energy particles are better understood through mechanical models utilizing billiard balls!

True, the early 20th century saw the collapse of Newtonian mechanics, since Newton's laws were shown to be unsatisfactory over very small distances, and at very high velocities. Even the Newtonian theory of gravitation was found inadequate, and was replaced by the General Principle. And it is also true that, as important as Newtonian mechanics is, it does not represent an accurate picture of modern physics. In fact it can present an extremely distorted view of the world. For according to Osborne (1990), it fails "to meet one of the first aims of physics education--to present an ontology of the physical universe answering the child's question--what is the world like?" (p. 191).

Yet, it should be recognized that it is the way it is presented and not the Newtonian mechanics itself that gives this "false" picture of the world. For although Newton's model is based on the determinism of the seventeenth century natural philosophy, it is mainly the imposition of the correct answer to a given problem situation that overstresses this determinism. And apart from this argument, we have to accept the fact that the uniqueness of Newton's intellectual achievement still exists. It cannot be discarded as an obsolete theory, since it gives accurate solution to an immense number of problems. And despite the shift of the paradigms, the fundamental questions that were posed by Newton have remained the same. For as Einstein himself commented:

> No one must think that Newton's great creation can be overthrown in any real sense by this or any other theory. His clear and wide ideas will forever retain their significance as the foundation on which our modern conceptions of physics have been built. (Einstein, 1950, p. 58)

Assumptions

1. Human understanding is a complex process that is not quantifiable.

2. Students understand when they become emotionally involved of their own free will.

3. Understanding is the result of imaginative restructuring of ideas and experiences students already have rather than the taking in of new ideas.

4. Students show what and how they understand by putting into relationship all the possible factors that might be involved in a given problem situation.

5. Understanding is contextual and can be assessed only through a wide variety of problem tasks referring to the same concept.

Delimitations

1. The present study was descriptive explanatory and its findings can be generalized only to a population with similar prior conceptions, beliefs, and expectations.

2. The present study was qualitative and therefore no statistical information was produced.

3. The participants were all volunteers but received 10 course grade points.

Limitations

1. The emotional state of the students, that is, their degree of involvement and the desire to actively construct meaning, could not be controlled.

2. The interaction between the interviewer and the students resulted in a negotiation of meanings and understanding in the form of a conceptual change.

3. Prior propositional knowledge might not have been activated through the problem tasks used in the study.

Definitions of Terms

1. Advance Organizer: Brief statement formulated in terms that are already familiar to the learner, and which is presented at a higher level of abstractness, inclusiveness, and generality. It helps subsume other less inclusive and more specific concepts and propositions. They act as mental bridges that connect prior with new concepts (Ausubel, 1965; Ausubel, Novak, & Hanesian, 1978).

2. Analogical Representation: It is a representational format of knowledge in which accurate images of original scenes are maintained (Norman & Rumelhart, 1976).

3. Cognitive Structure: Organization of concepts in the mind that acts as a mechanism in one's interaction with the external world (Piaget, 1970).

4. Concept: Regularity in naturally occuring or man-made objects (entities) and events (happenings) (Novak & Gowin, 1984).

5. Constructivism: A perspective which holds that knowledge, rather than passively received, is actively constructed in one's mind. The constructions can be either the representations of an autonomous real world to which we must fit or "accomodate" (Piaget, 1970), or the viable explanations of personal experiences (von Glasersfeld, 1989). An important implication of the latter constructivist perspective is the existence of a plurality of worlds rather than a single ontological reality (Goodman, 1984; von Glasersfeld, 1987). The constructivist perspective also holds that what is constructed in a given situation depends as much upon one's prior concepts and beliefs, as upon the characteristics of the context of each particular situation (Driver & Oldham, 1986).

6. Episodic Memory: Memory that receives and stores information about temporally dated events, and temporal-spatial relations among these events (Tulving, 1972).

7. Frame of Reference: A system relative to which motion is analyzed. It is chosen in such a way that collection and analysis of data are more easily accomplished. An inertial frame of reference is a frame of reference moving with constant velocity (Alonso & Finn, 1970).

8. Integrative Reconciliation: The process whereby two or more concepts are seen to relate to each other in a new way. It occurs when explicit effort is made to explore relationships between concepts and propositions, and to point out significant similarities and differences in order to reconcile real or apparent inconsistencies (Ausubel, 1965).

9. Knowledge: The result of the construction that begins with propositions between the concepts one already has and new concepts (Novak & Gowin, 1984), through an interaction with the physical and social world (Driver & Oldham, 1986). It is public and is shared by others (Gergen, 1982). It can be declarative--that is knowing "that"-- procedural--that is knowing "how" (Rumelhart & Norman, 1981), or conditional--that is knowing the conditions under which a rule or concept are applicable (Prawat, 1989).

10. Meaning: A construction taking place within the short-term memory where organized knowledge retrieved from the long-term memory interacts with new concepts (Wandersee, 1992), and it is personal and idiosyncratic (Johnson, 1987; Polanyi, 1958).

11. Newtonian Model: A representation of phenomena of force and motion based on four distinct components of human experience, namely, matter, motion, absolute space, and absolute time. Central to the model is the relativity of motion, and the idea that motion at constant velocity can take place even in the absence of a net force, and therefore rest and motion at constant velocity are fundamentally equivalent (Hadzigeorgiou, 1987).

12. Preconceptions: Ideas which are at variance with those of the scientists. They result both from personal experience and from an incorrect assimilation of scientific theories. They are often referred to as common sense theories, common sense beliefs, misconceptions, alternative conceptions, alternative frameworks, intuitive theories, naive theories, and children's science (Driver, 1991; Dykstra et al., 1992; Gilbert & Watts, 1983; Halloun & Hestenes, 1985).

13. Progressive Differentiation: The process whereby concepts are being constantly modified in order to acquire more meaning. (Ausubel, 1965).

14. Propositional Representation: A manner by which we retain our knowledge about the world. It is a representational format in which concepts are expressed as statements about the relationships among the concepts (Norman & Rumelhart, 1976).

15. Reality: Whatever constructs exist in one's Cognitive Structure, and through which one interprets and reinterprets one's experiences (Driver & Oldham, 1986). This definition does not differentiate between a Reality existing "out there" and a Reality of which people become aware. If a differentiation is made, however, the latter could be called Actuality (Fischer & Aufschnaiter, 1993).

16. Schema: Abstract propositional structure taking the form of a mental image that is developed through sensorimotor experiences (with motion and forces) at a very early age (Johnson, 1987), and also reinforced by everyday language (Osborne, 1984; Solomon, 1987; Viennot, 1979). As more experiences and concepts are acquired the schema evolves and takes the form of a hierarchically organized structure. This structure can also represent a single concept, object or event, according to a slot structure, where slots specify values that the concept has on various attributes (Anderson, 1985).

17. Semantic Memory: Memory about words and other verbal symbols, their meaning, and their relations among them (Tulving, 1972).

18. Strategy: Reasoning method employing a number of factors involved in a given problem task (Maloney, 1985).

19. Subsumption: The process whereby new knowledge is incorporated into more general concepts or propositions (Ausubel, Novak, & Hanesian, 1978).

20. Understanding: Mental activity that involves an attempt to relate a new piece of information to an established schema (Carey, 1986; Resnick, 1983). However, the following are also involved:

a. Expectations to form meaning (Bruner, 1986; Fischer & Ausfchnaiter, 1993; Wheatley, 1991).

b. Emotions (Norman, 1981, Scheffler, 1991).

c. Freedom and responsibility to construct meaning (Kelly, 1970).

d. Sharing of meaning (Mead, 1932; Solomon, 1987; Wheatley, 1991).

e. Relationships among concepts (Bruner, 1963; Karplus, 1981; Novak & Gowin, 1984; Prawat, 1989; Resnick, 1983; Scheffler, 1991; Wandersee, 1992).

f. Ability to use of a concept in multiple contexts (Bowden et al., 1992; Nickerson, 1985).

CHAPTER II

REVIEW OF THE LITERATURE

This chapter consists of four major parts. In the first part there is a discussion of the fundamental problem of human understanding as well as some of the limitations inherent in the problem itself. This part does not provide an in-depth review of the related literature--this would require an excursion into the philosophy of cognition over the past twenty or so centuries. Instead, it demonstrates some of the difficulties with which any researcher on human understanding is confronted. Moreover, an argument about how one might approach the problem of human understanding, despite those difficulties, is also raised. In the second part there is a review of the epistemological foundations of constructivism. The purpose of this part is to present, through a discussion of the fundamental ideas of Vico, Kant, Piaget, and Kelly, the constructivist model of knowledge, which, as it is argued, is in line with development of scientific concepts. The third part provides a synthesis of ideas about how humans understand. The purpose of this part is to discuss findings from cognitive psychology that give support to the constructivist model. Finally, the fourth part provides an in-depth review of the literature on student conceptual understanding in the area of force and motion. Starting from the pioneering work of Jean Piaget, this section discusses student preconceptions as have been identified by researchers worldwide. The purpose of the discussion of preconceptions is to draw attention to the importance of their awareness by physics instructors.

Part 1: The Problem and the Limits of Human Understanding

The problem of human understanding is certainly not a new one. Each generation, from the time of Plato to the present day, has reformulated the detailed epistemological questions in its own terms. However, the central guiding problems have remained the same: "How do we come to know?," "What sort of things do we know?," "To what extent do our senses determine what we know?," "Do our prior concepts, if any, predetermine our ability to acquire new knowledge?," and "Is there any difference between knowing and understanding?"

Nowadays most of the interest in student conceptual understanding is, hopefully, to answer the same epistemological questions about knowing, knowledge, concepts, and understanding. Yet, researchers on human cognition are faced with a problem simply because they do not "really" know what to look for when doing research on conceptual understanding. For any serious attempt on their part to define such terms is bound to leave them in the dark.

Current views in cognitive science and science education involve what is called conceptual change rather than conceptual growth (Brown & Clement, 1989; Dykstra et al., 1992; Gorsky & Finegold, 1992; Posner et al., 1982). In sharp contrast to behaviourist views, the current constructivist perspective places emphasis on mental reorganization rather than "mental saturation." Understanding seems to take place not so much through the taking in of new knowledge, as through a restructuring of ideas we already have (Driver & Bell, 1986). The history of science explicitly testifies to this fact. Kuhn (1970) challenged the traditional view of science as a continuous accumulation of knowledge, and suggested paradigm shifts which overturn much of what has been taken as "true" before.

However, such mental restructuring and paradigm shifts in the concepts of people, be they scientists working at the frontiers of knowledge or students in a classroom, do not take place spontaneously. Nor is it an easy and straightforward task to assess them. It seems that the search for knowledge does not involve rules, standard hierarchies of processes, but instead factors unique to the particular individual seeking knowledge and understanding (Millar, 1988; Polanyi, 1958). There are arguments that show the immensity and complexity of the problem of human understanding.

The Nature of Knowledge and Understanding

Russell (1948) expresses the view that knowledge is something vague and it is a matter of degree, while Popper (1974) argues that even scientific knowledge, that is, our best knowledge, is purely conjectural. Toulmin (1972) also points out that "the precise meaning of the terms concept and conceptual is rarely made explicit and frequently left quite obscure" (p. 8). In addition, understanding and knowledge are intimately related to beliefs, intuitions, and expectations (Russell, 1948), and any philosophical analysis, both metaphysical and epistemological, will unlikely provide us with any definitions.

No doubt, there is a close link between knowledge and understanding, since the latter presupposes the former. Moreover, the more knowledge one has the better one's understanding. Yet, one need not know everything there is to know about a specific concept in order to understand it. Our day-to-day communication is based upon such an "understanding." However, a thorough understanding of a concept is impossible simply because that would require knowledge of everything to which it relates (Nickerson, 1985).

It becomes quite apparent that in attempting to arrive at an acceptable definition of knowledge and understanding many contradictions begin to emerge. And the paradox, as had been identified by Socrates, is that the more knowledge one has about a certain aspect of the world, the more aware one becomes of the extent of one's ignorance. Understanding in this sense is equated with confusion, which, however, according to Nickerson,

> does not mean that one's understanding actually decreases but simply that one's appreciation of the complexity of that aspect of the world is likely to increase, which may be, after all, a better understanding of a fundamental sort. (Nickerson, 1985, p. 230)

But although Nickerson's (1985) point is well taken, the problem of assessing human understanding still remains a challenge. Does any person who is confused demonstrate an understanding? The only possibility available, as has been pointed out by Trowbridge and McDermott (1980) in their study with physics students, is to assess the "degree" of understanding:

> We may consider as an indicator of degree of understanding the extent to which a student's understanding corresponds to that of a physicist, i.e., the extent to which the student can define a particular concept in an acceptable operational manner, distinguish it from related, but different, concepts and apply it successfully. (Trowbridge & McDermott, 1980, p. 1,020)

It seems that this "indicator of degree of understanding" can take us out of our dilemma. The problem though is that it is the "number" of "successful applications" of a concept that will determine its understanding, and, therefore, an abstract mental process is reduced to quantifiable terms. And in such a case, a scale, probably based upon a certain number and types of applications, with a "minimum amount of understanding," will determine the degree of a person's understanding. The question, however, is "who," and "by what standards," will select the number and the types of applications.

Believing and Understanding

Beliefs, according to Polanyi (1958), are "the source of all knowledge" (p. 266), and even "truth is something that can be thought of only by believing it" (p. 305). Evidence, of course, for such statements can be found in the developmemt of major scientific theories. Metaphysical beliefs about the universe played a major role in Einstein's thought, and Galileo held on to his conviction about the motion of the earth despite the fear of imminent death.

But can we say that all people who understand such theories believe in them? Do people believe in the Big Bang or the the theory of evolution? For there is a distinction to be made between those who have the commitment and the intellectual passion to search for a pre-existing truth, and those who just understand theories, concepts, and symbols without necessarily believing them. According to Goodman and Elgin (1988),

> Whereas knowledge typically requires truth, belief, and substantiation, understanding requires none of these. Statements can be understood regardless of their truth and regardless of belief in them. (Goodman & Elgin, 1988, p. 161)

Driver and Oldham (1986) speaking from a pedagogical point of view "believe" that understanding is not the same as believing, since "it is possible to construct a meaning to generate a way of seeing something" like "phlogiston theory, without accepting it" (p. 110). Yet, here there is a paradox. For if it is accepted that knowledge is constructed by the individual in his or her attempt to understand the world, then all knowledge can be seen as beliefs which are tenaciously held (Dykstra et al., 1992).

There is a difference between the belief in "a force acting on a baseball traveling through the air" and the factual statement "nuclei are composed of protons and neutrons." The former is constructed by individuals themeselves, while the latter can be retrieved from a textbook, or imparted by a teacher during instruction. And regardless of whether or not the factual statement about the composition of nuclei is taken as true, a force in the direction of the baseball's motion is understood and taken to be a true belief!

<u>The Emotional Dimension</u>

Emotions seem to be intricately related to cognition (Bower, 1981; Norman, 1981; Scheffler, 1991; West & Foster, 1976), and matters become even more complicated. Polanyi (1958) provides strong arguments for a "personal knowledge" with an emotional tacit dimension that cannot even be assessed.

> Into every act of knowing there enters a tacit and passionate contribution of the person knowing what is being known, and . . . this coefficient is no mere imperfection, but a necessary component of all knowledge. All this evidence turns into a demonstration of the utter baselessness of all alleged knowledge, unless we can wholeheartedly uphold our own convictions. (Polanyi, 1958, p. 312)

The Hierarchy of the Cognitive Domain

Certainly, Bloom's work on the "Taxonomy of Educational Objectives" (Bloom, 1956) did throw some light in the area of human understanding, and particularly the cognitive domain. But his compartmentalization of the thinking process has its own problems too. No doubt, "Comprehension" requires a person to do more than memorize information. But do students say that "forces act in the direction of motion" because they have memorized every piece of information, word by word, about "forces" and "motion?" Do students not really "Comprehend," and therefore explain in their own words, why "heavy bodies should fall faster than light ones?" Do students not understand, since it makes sense, that once they stop applying a force on a body, the body stops moving, and therefore "all motion implies a force in the direction of motion?" Although all these are common sense beliefs, and should be considered "serious alternative hypotheses" (Halloun & Hestenes, 1985b), they are nonetheless at variance with what the teacher is supposed to teach. According to Bloom's (1956) model, students can move on to the Application level, since they have the prerequisites required at the Comprehension level. However, unless conceptual change takes place while students are at the Comprehension level, it would be meaningless to ask them to apply a concept or principle to other situations. In addition, it would be more appropriate to speak of levels of understanding, where "students move from one level . . . to another more complete one" (Bowden et al., 1992, p. 263), rather than of Comprehension, Application, and so forth.

On the other hand, is "Application" or "Analysis" so different, or even at a higher level in the taxonomy, from "Comprehension?" Is it not true that sometimes we have first to analyze in order to understand? Is it not true that we understand better by using a variety of applications, and that we do make evaluation judgements even before we become willing to understand?

In problem-solving under conditions of uncertainty where there seems to be no right answer, or no information available, judgements based upon assumptions about knowledge and reality are the first, if not the only, means to understand a situation (Kitchener, 1983). Evaluation judgements that make one decide about what is more relevant to a given problem situation played the most important role in the development of conceptual models and scientific theories. Ignoring friction, shape and colour of objects, and describing motion as change in position of dimensionless particles in 3-D space, was a judgement that was not based upon any current knowledge about motion, forces, and the nature of matter.

<u>Understanding and Hemispheric Preferences</u>

Problems, however, seem to exist even with the Learning Style Inventory developed by Kolb (1985), and the 4MAT model developed by McCarthy (1990). The latter, acknowledging Kolb's contibution, argues that there are "those who perceive in a sensing/feeling way" and who "project themselves into the reality of the now," and "those who think through experiences" by attending to the "abstract dimensions of reality" (p. 31).

But although it can be true that people have hemispheric preferences when perceiving and processing information, there is a question about the validity of the model with its four quadrants. Can it be so simple that people should fall within those quadrants? Can an individual not be both a thinker and intuitor, or both a feeler and thinker? Can an individual not belong to all those four categories, depending upon the particular task and the circumstances? In addition, is perception quite separate from processing? Do "reflective observation" and "active experimentation," as the ends of the processing continuum, not involve some thinking, which is only one end on the continuum of perception?

It sounds reasonable that, since the human mind invents models that can explain the world, it can invent a model of itself too. But perhaps this might be the only model that cannot be invented. Which feature of the human mind should be included, or excluded, so that it can best represent "the real mind?" And who, and by what standards, should make the decision? In the end it becomes evident that even this model of the mind represents a personal belief of his inventor!

<u>The Piagetian Model</u>

It should be stressed that Piaget's biological model (Piaget, 1972a) consisting of three separate phases, namely, assimilation, disequilibration, and accomodation also poses problems. The reason for this is that it does not necessarily explain human understanding. It seems that the disequilibration that results from the dissonance between existing concepts and experiences that explicitly contradict these concepts can help us understand. Yet as research by McCloskey (1983) showed, even college students failed to give the correct answer to problem situations that seem to have provided rich opportunities for accomodation and reflective abstraction. These findings undermine the Piagetian model, for they show that even motor activities that are done sensori-motorically, reflectively are known poorly.

But there is further evidence that undermines Piaget's model. For as research has shown (Driver et al., 1985; Johnson-Laird, 1983), children, through early experiences, build models or conceptual schemata in order to understand what is going on around them. Most of the time though these models and schemata are at variance with those of the scientists, despite the fact that children do seem to understand and explain the world! In short, autonomous cognitive development, as postulated by Piaget, does not necessarily lead to understanding since it can lead to the construction of "false" knowledge. This, of course, may sound self-contradictory, but knowledge and understanding have also a public dimension that complements, rather than contradicts, Polanyi's personal component. This can be also seen in Popper's (1972) three worlds: the world of perception, the personal world of mental constructions, and the public world of knowledge as documented in reports, books, and journals. The interrelationship between the personal and the public dimensions of knowledge and understanding is stated by Johnson (1987):

> To know is to understand in a certain manner, a manner which can be shared by others who join with you to form a community of understanding. (Johnson, 1987, p. 206)

The Conceptual Structure of Knowledge

Bruner (1963) and Hirst (1973), although speaking from different perspectives--the former as a cognitive scientist, and the latter as a philosopher--see understanding as involving the grasp of the structure of a discipline. But what is the structure of a scientific discipline like Newtonian mechanics? Accepting current views about the nature of reality and human knowledge (Gregory, 1988; Manicas & Secord, 1983), it becomes obvious that it is the human mind itself that constructs the structure or the logical organization of a discipline. If, of course, it is implied that "grasping the structure" is equivalent to helping students assimilate the structure with which a certain subject like Newtonian mechanics is presented in a book, two things can happen: either the students assimilate the structure of the book in a rote fashion, or they construct their own meaning, and therefore structure, by taking into account their prior conceptions. However, in the former case understanding will never take place, and in the latter every student will have his or her own structure which might be different from that of the textbook's or the teacher's. But the question remains: do those students who constructed their own conceptual organization "see the structure", as Scheffler (1991, p. 36) suggests? It is not very clear whose structure the student is supposed to see, because Scheffler himself says that the structure of a discipline is not what the author says or means.

Hirst's (1973) arguments for understanding by having the fundamental concepts of a discipline have their problems too. For it would be difficult to isolate certain concepts, particularly of a scientific discipline, and "term" them fundamental. For example, which concept of the Newtonian model is more fundamental? Force, or motion, or both? It is quite apparent that motion is more fundamental if one starts inductively, and force becomes the fundamental concept if one starts deductively. It might seem, of course, that the argument could be settled if it were accepted that both are fundamental. Yet it could be further argued that space and time are more fundamental than both force and motion since, according to Kant, these two concepts are "a priori." In fact, Kant does not even call them concepts but forms of intuition (Russell, 1948, p. 708). The only one who could settle this kind of argument is Newton himself, who based his model on the four distinct components of human experience, namely, matter, space, time, and motion (Hadzigeorgiou, 1987). Yet, his starting point was motion, since induction played a major role in his work.

But would motion, as a starting point, be a guarantee for understanding? Would induction, as was used by Newton, result in understanding? It seems that if one were to follow Newton's logic of reasoning in the classroom, two strategies would be appropriate for understanding. First to instruct or train students how to observe phenomena of motion, and second to start the teaching of the Newtonian model by introducing the concepts of length and time, and then move on to velocity and acceleration. At the end, the concept of force would be introduced and everybody could be confident that understanding has taken place. So far, however, both approaches have not helped students to understand (Ausubel et al., 1978; Shelley, 1989). For, on the one hand, observations are theory laden and are always preceded by a hypothesis (Popper, 1972); and on the other, the direction of cognition does not take place from simple concepts to the more complex concepts and principles but rather in the opposite direction, from a general problem to the specific concepts and principles involved in the problem (Ausubel et al., 1978).

Linguistic Meaning

Toulmin (1972), in his seminal work on human understanding, has argued that, although each of us has his or her own thoughts, our concepts are necessarily and inevitably shared. And yet, this sharing of concepts within a certain social context poses a problem, since there is the inescapable subjectivity of linguistic meaning. For as Glasersfeld (1989) has pointed out,

> We can no longer maintain the preconceived notion that words convey ideas or knowledge; nor can we believe that a listener who apparently "understands" what we say must necessarily have conceptual structures that are identical with ours. (Glasersfeld, 1989, p. 134)

It is quite evident that understanding through linguistic communication, oral or written, necessitates an active construction of meaning on the part of the listener or reader. However, there is no guarantee that such an understanding will take place, unless the listener or reader has built a conceptual framework that is compatible and fits--not matches--with the speaker's or author's conceptual framework. This fit, though, "manifests itself in no other way than that the receiver says and does nothing that contravenes the speaker's expectations" (Glasersfeld, 1989, p. 134).

Ogden and Richards (1956), starting from the premise that human communication involves thoughts (mental processes), words (symbols), and things (referents), have pointed out the problems, complexities, and ambiguities associated with linguistic meaning which always requires a personal interpretation of a sign or symbol. They have also noticed that: (a) meanings can be denotative and connotative, something any physics teacher is aware of when acceleration is taken to mean only an increase in speed, although in mechanics it refers to both increase and decrease, as well as change in direction, (b) definitions are contextual, since "they are relevant to some purpose or situation" (p. 111), and (c) meanings can be symbolic and emotive. In regard to the last differentiation between linguistic meanings, Odgen and Richards (1956) remark that,

> In symbolic speech the essential considerations are the correctness of the symbolization and the truth of the references. In evocative speech the essential consideration is the character aroused. Symbolic statements may indeed be used as a means of evoking attitudes but when this use is occurring it will be noticed that the truth or falsity of the statements is of no consequence provided that they are accepted by the hearer. (Ogden & Richards, 1956, p. 239)

Intellectual Relativism

Leaving aside beliefs, emotions, and their relation to human understanding, there are still problems if one takes into account the effect of language, and accepts the evidence that tends to justify linguistic relativism (Choi & Bowerman, 1991; Mori, Kitagawa, & Tadang, 1974). The work of Talmy (1975) also shed enough light on how different languages combine different notions to form meaning and words. In fact, these studies reconfirm what both Toulmin (1972) and Bernstein (1983) have stressed: that there is no permanent and neutral conceptual framework that can provide us with a rational judgement. It is therefore crucial that the evaluation of an individual's conceptual framework take place by an individual who speaks the same language, and belongs to the same culture as well.

However, the problems with relativism do not end here. For in looking down the history of mankind, it becomes evident that ideas about how humans understand are inevitably shaped by ideas about the world prevalent at a particular time. Plato's approach was purely philosophical, and therefore speculative. Descartes and Locke, although critical thinkers, were also men of their time who approached the problem of human understanding from the perspective of current ideas about physics, physiology, and psychology. Therefore they both studied epistemological problems in the light of the prior conceptions about a fixed order of Nature, and an inert matter that was distinct from a rational mind (Toulmin, 1972).

Dewey's concepts about Darwin's theory of evolution also played a major, and perhaps the most important, role in his thought, as it can be seen in his Experience and Education (1938) and How We Think (1933). It is no coincidence that thinking and learning, as integral parts of the knowing process, have evolved because they both have a vital function--namely the survival of man in the struggle of life. It is therefore obvious that his pragmatism and his instrumentalist theory of truth are the results of, and at the same time rooted in, a practical view of knowledge. And Piaget is no exception. Although a genetic epistemologist, his earlier training in biology did have a profound effect upon his subsequent philosophical thinking. Not only the terms assimilation, equilibration, and accomodation, but also his idea of postulating the construction of cognitive structures in a developmental way, show the influence of biology.

At present, constructivist views about the nature of knowledge, reality, and understanding are gaining acceptance, and we also view the human mind as an information processing machine. But the question remains: what intellectual authority does the thinking of Plato or Descartes have over that of Dewey or Piaget or the modern constructivists? For if we accept the fact that "we are brought up with certain ideas about society and morality, about geometry and algebra, about matter and the universe" and "we learn to regard certain methods of investigation and types of arguments as rational or scientific, and others as superstitious or muddle-headed" (Toulmin, 1972, pp. 50-51), would it not be true that our modes of thought can be as much reflections of our particular time and place in history as our modes of social behaviour?

Twenty years or so ago the human brain was believed to be compartmentalized into three different and separate domains, but at present the holistic mechanism of cognition is gaining acceptance. And the idea that brought about the cognitive revolution, namely that the human brain is nothing more than a computer is currently criticized (Scheffler, 1991).

Following this line of reasoning, no rational authority appears to exist, and no claims can be made on behalf of the ideas of Plato or Dewey as compared with those of today's or tomorrow's cognitive scientists. Therefore the question "who is right?" seems to be meaningless.

Approaching the Problem of Human Understanding

Having discussed the complexities associated with human understanding, the most plausible question that might be asked is how one might approach it. At first glance this appears to be a difficult, if not an impossible, task. Given in addition the fact that an assessment of human understanding will inevitably involve personal interpretations, the validity of that assessment seems to be called into question. Yet, what is consoling is that we have at our disposal a rich store of knowledge that has been accumulated over the past 2000 years. And more consoling, as a consequence, is the fact that we know more than any of those past thinkers who approached the same problem. This knowledge though is a powerful tool provided that neither a relativist nor an objectivist approach is adopted, and therefore a coherent system of ideas is established.

Although we will inevitably approach the problem of human understanding from our current perspectives about the world and human nature, we should be careful not to fall into the trap of relativism. Nor should we adopt an absolutist view of our, or any, intellectual authority. After all, Plato seems to have been justified by modern cognitive scientists who stress the importance of "prior," though not "innate," ideas. And the early Gestalt psychologists, who had focused on "wholes" rather than parts, seem, at least at present, to have been in the right. Even Locke's "sense experiences" do play a major role in the knowing process, although we do not consider the mind as a "tabula rasa" any more.

However, although we do not have an absolute authority over previous thinkers, we are at a better vantage point to make cross-contextual judgements about the various approaches to the problem of human understanding. The findings of modern cognitive science as well as those of neurophysiology cannot be ignored. Nor should rational cross-comparisons be dismissed as meaningless. Certainly, due to their different linguistic, cultural, and conceptual frameworks, Plato and Piaget appear to have no common points of contact. But would Plato not agree that infants possess an intelligence, and, by actively exploring their environment, do in fact learn something about the world? It is quite certain that Plato would not have dismissed that, despite his insistence that "true knowledge" is only a recollection of Ultimate Reality (Plato, Republic). And would modern constructivists not agree with Plato that for an understanding of our own reality we have to "look inside" rather than "outside ourselves?"

The attraction of intellectual relativism remains very strong. But it should be stressed that there are several points of contact among all those thinkers who approached epistemological problems. And the fact that Plato's epistemology has strands that appear in today's journals of cognitive psychology do show that neither an objectivist nor a relativist view of human understanding will prove fruitful. Some ideas are rejected, some are retained, and some are modified; and in such a way knowledge grows.

Today of one thing we are almost certain: that knowledge "was not there" one day; it has grown. And this growth was the result of two complementary activities: looking inside and looking outside ourselves.

> Looking outside ourselves and mastering the problems by the world we live in, we have extended our understanding; looking inwards and considering how it is that we master those problems, we have deepened it. And throughout the history of thought these twin activities have gone continuously in parallel. (Toulmin, 1972, p. 1)

It is true that ever since the dawn of western civilization the pendulum of history has been swinging back and forth, between two extreme positions, and mankind has been thinking in terms of extreme opposites. At one time there was just one ultimate reality, and at others many; at one time knowledge was due to innate ideas and at others to sense experiences; and at one time God seemed to play dice with the universe and at others he did not. However, it is time we recognized that Either-Or philosophies are not going to be fruitful. Deciding between objectivism and relativism, or between rationalism and empiricism, is not going to help us approach, let alone "understand," the problem of human understanding.

There seems to be no reason for us to assume that there are no linkages between Descartes and Dewey, or between Plato and Piaget. For despite the effect of several centuries of conceptual change, and therefore the different conceptual frameworks that separate them, their fundamental epistemological positions have remained the same, and their theoretical positions are not totally unbridgeable.

The progress in science provides strong evidence against both relativism and objectivism, since this progress was the result of a continuous process of falsification and modification rather than the acceptance of ideas, either from a relativist or absolutist point of view. Scientists did not remain "trapped" in their own worlds. For different paradigms do not necessarily imply that there is no common ground among them. Kuhn (1970) adopts a relativist approach, which, however, does not explain how communication among scientists working within different paradigms, and therefore how scientific progress, become possible (Sayers, 1982). Although there is no "God's Eye" view, and value-free framework of the world, although there is no ahistorical matrix of human rationality, we cannot accept the idea that "any" individual can have "any" idea about the world. Conceptual change and paradigmatic shifts have resulted within a social and historical context, and it does not follow that "anything goes." For although "judgements are not reduced to simply a matter of taste, opinion, or emotive reaction . . . in an anything goes sense", our concepts "must be understood as relative to a particular conceptual scheme . . . society, or culture" (Smith, 1988, p. 18).

It should be recognized that without something that can be taken as a standard, no comparisons, and therefore no judgements can be made. Even in the theory of relativity the speed of light was taken to be an absolute fixed standard, regardless the relative interpretation of space and time. By the same token, there is a fixed standard against which to judge human rationality and understanding. This standard, though, is not only shared within the context of history, language, and culture, as Johnson (1987) argues, but is also personal. This may sound self-contradictory, but the complementarity of this personal meaning and public understanding provides us with a fixed standard, and that is the coherence and fit of our beliefs and knowledge. These beliefs and knowledge, in this sense, are not subjective, since they represent a synthesis of ideas about human understanding, and which themselves become accepted for their coherence and fit. For as Putnam (1981) has stated:

> What makes a statement, or a whole system of statements --a theory or a conceptual scheme--rationally acceptable is, in large part, its coherence and fit; coherence of "theoretical" or less experiential beliefs with one another and with more experiential beliefs, and also coherence of experiential beliefs with theoretical beliefs. Our conceptions of coherence . . . depend upon our biology and our culture; they are by no means "value free". But they are our conceptions of something real. They define a kind of objectivity, objectivity for us, even if it is not the metaphysical objectivity of the God's Eye view. (Putnam, 1981, pp. 54-55)

Accepting, therefore, "the inevitable consequence of our hermeneutical or interpretive mode of being in the world" (Smith, 1988, p. 18), we can judge how people understand according to our own rationality, that is, in terms of the coherence and fit of our arguments, but taking, nevertheless, into account the acceptable conceptual framework of our culture.

Part 2: Constructivism and Human Understanding

A current paradigm that explains how people, and particularly students studying science, understand is "Constructivism." Contrary to the hidden assumption that knowledge can be transmitted from a textbook or the mind of a teacher to the mind of the learner, the constructivist model of knowledge acknowledges the active role of the learner (Driver & Oldham, 1986; Wheatley, 1991).

> Knowledge originates in the learners activity performed on objects. But objects do not lie around ready made in the world but are mental constructions. We reason with scientifical objects which are our constructions. (Wheatley, 1991, p. 10)

The Philosophical Roots of Constructivism

According to Glasersfeld (1985, 1989), it was Vico, a Venetian philosopher, who provided the first exposition of a thoroughly constructivist epistemology with his treatise De Antiquissima Italorum Sapientia. Vico's central argument is that

> God is the artificer of Nature, man the god of artifacts . . . to know means to know how to make . . . one knows a thing only when one can tell what components it consists of. Consequently, God alone can know the real world, because He knows how and of what he has created it. In contrast the human knower can only know what the human knower has constructed. (Glasersfeld, 1989, p. 123)

The idea that knowledge originates in the learner's head is also evident from Vico's writings:

> Man cannot know the things that are in the world because their components lie outside man's mind, and man, therefore has no access to them and cannot use them to build up true knowledge. (Glasersfeld, 1985, p. 94)

If Vico's argument is taken into consideration, the fact that students have difficulty understanding science is explained. (It would be therefore unrealistic to expect students to understand the mental constructions of Newton, Einstein, Maxwell, or Plank. But it would be equally unrealistic to expext students to construct advanced concepts and models. This dilemma though is resolved once students are given the opportunity to act upon the environment, and, in the process, consider and reconsider ideas and thus construct knowledge.)

Kant (1934), on the other hand, was the first to argue that our concepts are mental constructions through which we interpret our experiences. But unlike Kant's idealism which postulated universal fixed concepts and categories, in constructivist terms, our concepts are both historically and socially determined. This is quite apparent in Weber's (1949) interpretive epistemology--based on the idea that concepts are constructed and reconstructed by individuals in their attempt to make sense of the world--as well as in the theories of quantum physics and relativity which have abandoned causality, permanence of matter, the classical conception of time, and the Euclidean interpretation of space. Unlike also Kant's approach to reality--that is, the things-in-themselves (noumena), and reason--that is, the things as they appear to be (phenomena), constructivism unites reason and reality: our concepts and categories both reflect and interpret reality, and there is, therefore, no difference between the "noumena" and the "phenomema." This unification of appearence and reality is central to the Hegelian epistemology which found Kant's metaphysical and unknownable thing in itself to be repugnant to an idealistic monism. However, unlike the Hegelian approach to reality which is objective and "shines forth" in order to manifest itself in appearence (Sayers, 1985, pp. 33-45), reality, as again Kant (1934) argued, is a purely mental product.

At present, three major constructivist epistemologies can be found in the literature; that of Weber (1949), that of Kelly (1970), and that of Piaget (1970). Weber's epistemology is briefly discussed in the section of the social dimension of knowledge, while the other two are reviewed in some detail below.

The Biological Theory of Jean Piaget

The constructivist approach to the study of cognition, after it was disregarded for two centuries, started with the work of Piaget who became concerned with the way children construct knowledge. His thesis is elaborated in his books Biology and Knowledge (1971a), Psychology and Epistemology (1971b), and The Principles of Genetic Epistemology (1972a). Although Piaget does not use the term "understanding" in his own writings, his answer to the two fundamental questions of genetic epistemology, namely, "what is knowledge?" and "how are the various types of knowledge possible?" (Piaget, 1971b), provides a new approach to the problem of human understanding.

Starting from the metaphysical premise that "all reality--biological, physical, psychological, sociological, intellectual--is evolving in the direction of progress" (Kitchener, 1986, p. 6), Piaget explains reason and understanding in evolutionary terms. This evolutionary explanation also leads Piaget to adopt the biological terms "assimilation," "accomodation," that is, two simultaneous processes occuring while the "organism," and hence the epistemic subject, interacts with the environment in order to satisfy its "epistemic needs," and "equilibration," that is, a state of equilibrium resulting from the satisfaction of those needs. It is obvious, according to this biological model, that the essence of cognition lies in its adaptive function. And through this function, the epistemic subject is progressing from one level of equilibrium to another, thus attaining a better understanding. Kitchener (1986), in an interpretation of Piaget's writings, also speaks of levels of understanding which are subject to an ongoing dialectical process. This certainly shows the Hegelian influence on Piaget's philosophical thinking.

In rejecting traditional empiricism and the copy theory of knowledge, as well as traditional idealism and rationalism, Piaget proposes that knowledge is constructed through the active interplay of experiences and the developing cognitive structures. These structures are not innate but are developed because of the way the human brain is designed to interpret the stimuli it receives. According to Piaget (1970, 1972a), cognitive development unfolds in much the same way a logical argument unfolds, step by step, in a logical sequence, and proceeds by means of four basic and distinct stages: the sensorimotor stage (0-2 years), the preoperational stage (2-7 years), the concrete operational stage (7-12 years), and the formal operational stage (12-15 years). During and throughout these stages, the child's cognitive structure might be regarded as a set of logical premises, and experience provides the information that the child uses to make deductions from his premises, resulting in a new set of cognitive structures, from which further deductions can be made, and so on until an adequate set of structures is acquired that enables the child to understand and cope with the world. This making of deduction after deduction from given cognitive structures leads to the construction of knowledge, and hence, to understanding.

The idea of autonomous construction of knowledge is different from both rationalism and empiricism, although it seems to be a combination of both. Something must be innate that allows for autonomous development. And external experiences must also play a major role in the interaction between people and their environment.

Piaget (1970) reports that cognitive structures exist even in deaf and blind children, although, due to the lack of sensory input, they develop much later. But reality is not eternal and unchanging, awaiting to be "recollected" by the knower. Nor is it "out there," awaiting to be discovered through the senses. Instead, reality, including "cognitive schemes, categories, concepts, and structures necessary for knowledge" (Kitchener, 1986, p. 102), is constructed through a personal interaction with the environment, and it is therefore a personal affair. It is evident that this kind of constructivism departs from the Kantian constructivism that postulated universal innate categories.

It would be worth mentioning that Piaget (1970, 1972a) equates intelligence and understanding with the development of increasingly logical, complex, and numerous schemata, which he defines as "the structures or organization of actions as they are generated by repetition in similar or analogous circumstances" (Piaget & Inhelder, 1969. p. 4). His essential contribution is the description of how those mature schemata, so numerous and complex, have evolved from infantile reflexes such as sucking and palmar grasping. Understanding is equivalent to incorporating an object into an already existing schema.

In discussing Piaget's ideas, it becomes apparent that at the heart of his model is the "action" of the "knowing" subject upon the "objects" of the world. This action upon an object can take two forms:

> One consists in modifying its positions, its movements, or its characteristics in order to explore its nature: this action is known as "physical." The other consists in enriching the object with characteristics or new relationships which retain its characteristics or previous relationships, yet completing them by systems

> of classification, numerical order, measure, and so forth: these actions are known as "logico-mathematical." (Piaget, 1971b, p. 67)

It becomes also apparent that "reality" and "knowledge" had for Piaget (1970) a special meaning. In regard to the former he accepted that it is known only when it is acted upon. This obviously shows his departure from the copy theory of reality of classical empiricism. In regard to the latter, he distinguished between two kinds of knowledge: empirical knowledge, that is knowing "about" the world through an abstraction from that world, and logico-mathematical knowledge, that is knowing about the intricate relationships of the actions upon the world.

Although it could be argued only logico-mathematical actions and knowledge result in understanding, the notion that the knower, or epistemic subject, is actively involved in any kind of action, makes one infer that even in empirical knowledge, that is, knowledge derived from physical actions, abstraction is an active affair. For as Piaget (1971b) repeatedly stresses, "we only know an object by acting on it and transforming it" (p. 67).

Kelly's Theory of Personal Constructs

An epistemology of the interpretive tradition is at the heart of Kelly's theory of personal constructs which stresses the fact that "whatever the world may be, man can come to grips with it only by placing his own interpretation upon what he sees" (Kelly, 1970, p. 2).

It is worth mentioning that the work of Kelly (1955) on the theory of personal constructs, initially published almost 40 years ago, offers a constructive perspective since it views the individual as a "scientist" who builds for him or herself internal models in an effort to understand and make predictions about events of the external world. These models are subject to modification, since construction of reality is constantly tested out so that better predictions can be made in the future. For Kelly human behaviour is anticipatory rather than reactive.

> The theory is based upon the philosophical position of constructive alternativism, the notion that there are many workable alternative ways for one to construe his world. The theory itself starts with the basic assumption, or postulate, that a person's processes are psychologically channelized by ways in which he anticipates events. (Kelly, 1955, p. 560)

Central to the theory of personal constructs is the notion that "the thoughtful man is neither the prisoner of his environment nor the victim of his biography" (Kelly, 1955, p. 560), but, instead,

> an inveterate inquirer, self-invented and shaped, sometimes wonderfully and sometimes disastrously, by the direction of his enquiries. (Bannister & Fransella, 1986, p. vii).

It is evident that, contrary to the deterministic ideas of both Freudianism and behaviourism, namely, that we are the victims of our infancy, and our reinforcement activities respectively, constructive alternativism views people as free agents able to construct their own reality, and take also the responsibility for such constructions.

> The very idea of construct, as distinct from a concept, is that it introduces criteria of relevance and responsibility. Action can only be subjected to moral judgement in the context of what a man might have done, as a field of choice around what he did, and perceptions, being selective, negate certain possibilities. We are then responsible for our construing since this is the formative structure of our choosing. (Holland, 1970, p. 125)

It becomes quite apparent that Kelly's theory of personal constructs shares with existentialism a number of features, as that of action--they are both theories of action--that of person--they both treat the individual as a person as opposed to an object or even a biological organism --and that of responsibility--Kelly himself equates the philosophical position of constructive alternativism with an "epistemological responsibility" (Kelly, 1970, p. 2). In fact, the notion of responsibility is an important one, for as Kelly further remarks,

> even the most valuable construction we have yet contrived--even our particular notion of God Himself--is one for which we shall have to continue to take personal responsibility, at least until someone turns up with a better one. (Kelly, 1970, p. 4)

Although Kelly's ideas have immense implications for a wide variety of fields, their consequences for conceptual, or rather "constructive," understanding are significant and far-reaching too. For accepting the notions of free choice and "epistemological responsibility," the idea that neither the reinforcement nor the motivational methods have worked so far becomes justified.

Constructivism and the Notion of Truth

As far as the notion of truth is concerned, coherence and fit, viability and usefulness are all united in a new constructivist epistemology.

> Facts are true, we may say, just so far as they work, just so far as they contribute to the order of experience. If by taking certain judgements of perception as true, I can get more system into my world, then these "facts" are so far true, and if by taking certain facts as errors I can order my experience better, then so far these "facts" are errors. And there are no "facts" which possess an absolute truth. (Bradley, 1914, p. 240)

It should be noted that while coherence and fit play a role in accepting or rejecting certain ideas and arguments "in accordance with how they cohere and fit with the rest of our ideas about reality" (Sayers, 1985, p. 136), the instrumentalist approach is taken as the main avenue to gaining knowledge. This approach leads to knowledge that is viable within our experiences (Glasersfeld, 1989) and is therefore similar, although not identical, to Dewey's inquiry method where viability and usefulness are blended in "the opinion which is fated to be ultimately agreed to by all who investigate" (Russell, 1946, p. 824).

The idea that there are no facts that possess an absolute truth is also central to the philosophical position of constructive alternativism. For

> even when events are reconciled with a construction we cannot be sure that they have proved it true. There are always other constructions, and there is the lurking likelihood that some of them will turn out to be better. The best we can ever do is project our anticipation with frank uncertainty and observe the

> outcome in terms in which we have a bit more confidence. But neither anticipation nor outcome is ever a matter of absolute certainty from the dark in which we mortals crouch. (Kelly, 1970, p. 4)

Contrary to the positivist tradition and the epistemological assumption of "accumulative fragmentalism," truth, according to constructive alternativism, is not to be collected piece by piece, nor to be judged in terms of whether a proposition can be proved true or not true, but instead in terms of whether a proposition can lead towards a new proposition (Kelly, 1970). And although we cannot say that one proposition or construction is better than any other, any new proposition

> must be regarded as a crude formulation of a question which, at best, can serve only as an invitation to further inquiry, and one that can be answered only through personal experience, and . . . the answer we get is not likely to be exactly an answer to our question at all, but an answer to some other question we have not yet thought to ask. (Kelly, 1970, p. 5)

Constructivism and Ontological Reality

The notion of the transformation of the epistemic object raises metaphysical questions regarding the nature of reality. For as in the theory of quantum mechanics where what is observed is the result of an interaction between the subject and the object, in Piaget's constructivism reality is constantly modified through the action of the epistemic subject on the epistemic object.

The metaphysical question that could be asked concerns the existence of the epistemic object, namely whether it exists independently of any constructions, or whether it can be constructed through the mental processes of the epistemic subject. It is quite obvious from such considerations that an independent existence leads to a realism, while an free construction leads to an idealism. However, as Kitchener (1986) points out, the interaction between subject and object presupposes their existence prior to interaction, and therefore, "Piaget's constructivism only makes sense if one is committed to some kind of metaphysical realism" (p. 114). In short, constructions for Piaget were representations of a real world to which children had to accomodate.

Constructivist views are held by recent philosophers and philosophers of science who reject the notion of the existence of objective observations against which any theory about the world can be checked (Goodman, 1984; Manicas & Secord, 1983). It is quite evident that this constructivist approach to cognition is different from Piaget's, since the latter seemed to cling to an epistemology of naive realism.

In defending a constructivist philosophy, Goodman (1984) puts forward the thesis that, contrary to the common-sense view that there is a unique real world which preexists and is independent of human mental activity, every aspect of the world, whether a constellation, a single star, or a chair, is the result of a conscious interaction between a previously made world and the symbolic procedures of a mind. In this way, man is not only the observer, but also the participator "in making the past, as well as the present and the future" (p. 36). Gregory (1988) has a similar view:

> There seems to be no already-made world, waiting to be discovered. The fabric of nature, like all fabrics, is woven by human beings for human purposes. (Gregory, 1988, p. 186)

Manicas and Secord (1983), share the same epistemology, since in our attempt to represent the world, we construct concepts which take on a reality, although "epistemologically, there is nothing known to which our ideas can correspond" (p. 401). This is eloquently and unambiguously epitomized by Einstein and Infeld (1938):

> Physical concepts are free creations of the human mind, and are not, however, it may seem, uniquely determined by the external world. (Einstein & Infeld, 1938, p. 31)

It is quite obvious from what Einstein and Infeld say, that, rather than viewing our observations as real, it is our constructions of the world which are real, in the sense that, through these constructions, we interpret and re-interpret our experience. Einstein and Infeld (1938) further tell us that at the heart of the knowing process is our attempt to build models, which, however, can never be compared with the external world, since "we cannot even imagine the possibility of the meaning of such a comparison" (p. 31).

Glasersfeld (1985, 1987, 1989) also states that the function of cognition is adaptive and serves the organization of the experiential world, not the discovery of ontological reality, echoing Bohr's own words: "It is wrong to think that the task of physics is to find out how nature is. Physics concerns only what we can say about nature" (cited in Peterson, 1985, p. 305). Glasersfeld (1989) stresses the fact that we cannot "check" our knowledge against an external reality. Our only check is the extent to which our constructions fit with our experience in a coherent and consistent way. Knowledge in this sense is "conceptual constructs" that are "viable in the experiential world of the knowing subject" (p. 122).

Glasersfeld (1985), in discussing the notion of "adaptation," points out that adaptation is misunderstood "as the process of a structure becoming more and more like whatever it is adapting to" (p. 96). On the contrary, a radical constructivism that postulates mental constructions that fit, rather than match, with reality

> does not require building blocks that are part of ontological reality, but . . . elements found in the knower's experiential world. (Glasersfeld, 1985, p. 97)

The Philosophical Strands of Constructivism

In discussing the epistemological roots of constructivism, it deserves to be noted that it has borrowed fundamental notions from all philosophical positions. A personal interpretation of the contribution of these philosophical positions with their respective notions could be as follows:

1. Formal Idealism: The human mind is the primary element in the construction of knowledge.

2. Absolute Idealism: The knower and the known are united and are in a dialectical process of becoming, reality is experience, and the primacy of the whole over its parts.

3. Rationalism: Belief in an innate structure (but not innate ideas) that develops through a rational order. (Contrary to Descartes and Leibniz, the mind is not fully formed at birth but is developed autonomously.)

4. Empiricism: Sense experience is necessary in the construction of knowledge, but it is not the only element present in this construction (as empiricism holds), since the latter presupposes a prior concept, schema, into which the sense experience will be assimilated.

5. Realism: An independent world exists but of which we have no knowledge (noumena).

6. Pragmatism: Knowledge is tied to action, reality is not something ouside of experience, and truth of knowledge is judged in terms of its utility (in the sense that it can explain and predict our experiences, and also provide knowledge for further inquiry).

7. Existentialism: Freedom of choice and responsibility for the construction of knowledge, reality exists only in action, and the meanings are shared since in their construction we have involved all humanity.

Part 3: What We Know About How Humans Understand

Granted that the current constructivist perspective places an emphasis on the reorganization of the conceptual structure, it is obvious that what really matters is what is in a person's head. Although a personal interpretation, this reorganization could be described by the prior conceptions and their inter-relationship, the schemata, the direction of cognition, as well as the emotions and the expectations of the epistemic subject. However, the social context in the construction of knowledge is also a factor to be considered.

Prior Concepts

The first to stress the importance of prior ideas was Plato who explicitly stated in one of his famous dialogues:

> I know, Meno, what you mean . . . you argue that a man cannot inquire either about that which he knows, or about that which he does not know; for if he knows, he has no need to inquire; and if not, he cannot; for he does not know the very subject about which he is to inquire. (Plato, Meno, p. 36)

That our prior concepts "turn out to be the instruments of effective thought" has been pointed out by Toulmin (1972, p. 35), and Ausubel et al. (1978) have explicitly stated in their epigraph that the single most important factor in understanding any new piece of knowledge is what the individual already knows.

Carey (1986), in discussing the implications of cognitive science for science education, remarks that:

> Students reading a science text or listening to a science teacher must gain understanding by relating what they are reading (hearing) to what they know, and this requires active, constructive work.
> (Carey, 1986, p. 1,123)

Popper (1972), arguing from a philosophical point of view, stresses the fact that knowledge never begins from nothing, but always from some background knowledge. "The growth of knowledge consists in the modification of previous knowledge that results either in its alteration or its large-scale rejection" (p. 71). Popper's ideas, in fact, echo what Plato (Republic) had remarked upon almost 25 centuries ago:

> We must reject the conception of education professed by those who say that they can put into the mind knowledge that was not there before--rather as if they could put sight into blind eyes. (Plato, Republic, p. 285)

The Stucture of Knowledge

Putting aside metaphysical questions about the nature of reality, as well as epistemological questions about the nature of knowledge, it is evident that there is an interaction between the "knower" and "what is to be known." The latter can be the subject matter of a discipline which has a certain structure. Hirst (1973) speaks, not of disciplines, but of "Forms of Knowledge" which have their own logical structure, and equates understanding with "having" this logical structure. The structure of physics, for example, is different from that of philosophy or literature, and therefore understanding will necessarily involve having each form's "distinctive logical structure." Bruner (1963) expresses a similar view, for he believes that conceptual understanding entails an understanding of the structure of the particular discipline. However, he sees structure in terms of relationships among concepts.

> Grasping the structure of a subject is understanding it in a way that permits many other things to be related to it meaningfully. To learn structure, in short, is to learn how things are related. (Bruner, 1963, p. 7)

Prawat (1989) and Scheffler (1991) also believe that structure is important. To understand a theory is "to see its structure, its organization, its references, its various interpretations . . . not what the author means, for an author may intend something not in fact said, and say something not in fact meant" (Scheffler, 1991, p. 36).

Novak and Gowin (1984), and Heinze-Fry and Novak (1991) assert that knowledge which is maintained in long term memory is not a series of isolated facts, but is highly organized and inter-related in multiple ways. This structure helps individuals integrate their knowledge, clarify the relationships among the various concepts, and spend less time in rote memorization. They propose concept mapping as a strategy that helps students develop this structured knowledge (Figure 1).

The importance of structured knowledge is stressed by Prawat (1989) who says that structure enhances knowledge accessibility. Resnick (1983) express the view that isolated pieces of information are meaningless unless they are organized into clusters of concepts.

Ausubel (1965, 1968) and Ausubel et al. (1978) are thinking along similar lines. They see understanding in terms of making meaningful relationships, that is, in terms of how meaningfully subject matter is related to existing general and abstract ideas that act as organizers. According to Ausubel (1968), organizers provide "ideational scaffolding for the stable incorporation and retention of more detailed and differentiated material that follows" (p. 148).

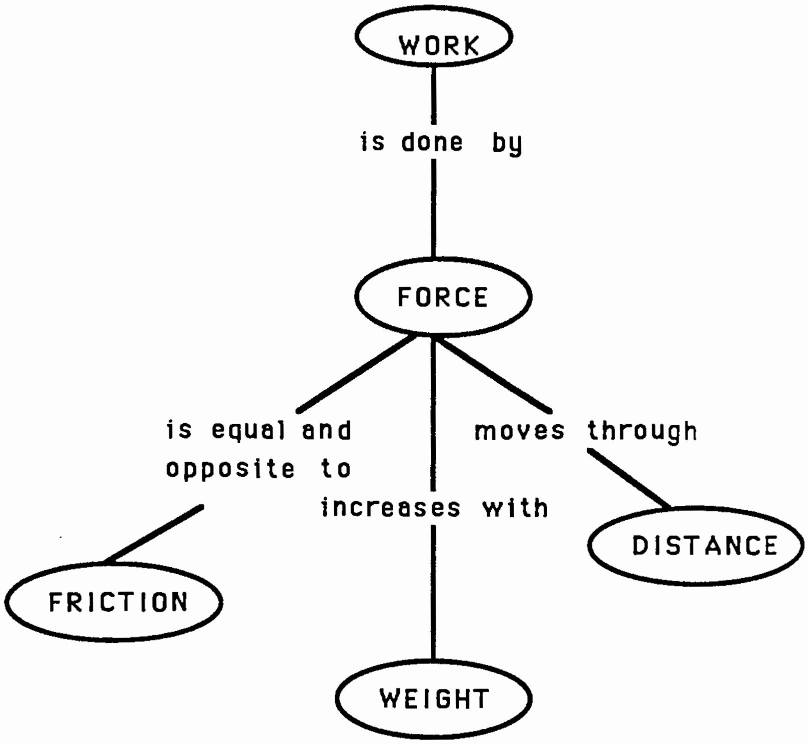


Figure 1. Concept Map Showing Relationship of Concepts Involved in Work Done when Pushing Box on Floor.

Having discussed the structure of knowledge due credit should be given to Vico's epistemological argument that "one knows a thing only when one can tell what components it consists of" (Glasersfeld, 1989, p. 123). It seems that the relationships among the concepts are the most important factor in human cognition, and their primacy had been pointed out by Dewey (1956): "a wagon cannot be perceived as a wagon even when all its individual parts are put together; it is rather the connections between its parts that make it a wagon" (p. 143). Phenix (1964), in his philosophical discussion of meaning, also pointed out that "meanings are relational" (p. 13). Although his analysis is concerned with the sharing of meanings in a community, the notion of "relational" gives further support to Vico's argument for the importance of relationships. In fact, Vico's idea, namely that knowledge of something implies knowledge of its components, could be extended by adding that the more relationships we have the better our understanding.

Basseches (1980) challenged Piaget's "formal operations" by suggesting that a transformation from formal thought to dialectic operations might be characteristic of cognitive development after early adolesence. In defining dialectic thought, Basseches (1980) stresses the primacy of conceptual relationships over other features of cognition.

> Dialectic is developmental transformation which occurs via constitutive and interactive relationships. . . . Although a relationship is often thought of as connection between things, where the things are taken to exist prior to the relationship, the phrase "constitutive relationship" is meant to indicate the opposite--that the relationship has a role in making the parties what they are. (Basseches, 1980, pp. 405-406)

The Context of Knowledge

Studies conducted over the last two decades have identified two major types of knowledge. Distinctions are being made between declarative knowledge, that is "knowing that," and procedural knowledge, that is "knowing how" (Anderson, 1985; Rumelhart & Norman, 1978; Rumelhart & Ortony, 1977; Tulving, 1972). Rumelhart and Norman (1981) argue that human knowledge has characteristics which are attributed to procedural rather than to declarative systems, since our ability to reason and use our knowledge seems to depend strongly upon the context in which the knowledge is required.

> Most of the reasoning we do apparently does not involve the application of general purpose reasoning skills. Rather it seems that most of our reasoning is tied to particular bodies of knowledge. (Rumelhart & Norman, 1981, p. 338)

Resnick (1983, p. 478) thinks along similar lines, since she stresses that "a person's intelligent performance, is not as a matter of disembodied processes of thinking, but dependes intimately on kind of knowledge a person has about a particular situation." Halloun and Hestenes (1985b) did in fact find that university physics students had difficulty in applying the same principle in two different contexts. For example, 60% correctly predicted a parabolic path of a projectile, but only 20% applied the same principle in the context of a rocket that was coasting in outer space. Brown and Desforges (1977) also showed that individual students do not operate at the same level of thought in different situations. And while Inhelder and Piaget (1958) had originally suggested that formal operations are independent of the content area in which they are assessed, Piaget himself (1972b) later acknowledged the importance of the context in the development and use of formal operations.

Glaser (1984) stresses the fact that the ability to retrieve the appropriate rule applicable to a particular problem situation is dependent upon the knowledge representation in memory. Bransford et al. (1986) also state that "competencies in a domain and the ability to think about the domain seem to develop hand in hand" (p. 1,080). There is evidence that differences between "mature thought" and "expert thought" can be attributed to the fact that "expertise" is strongly dependent upon both content-specific knowledge and task-specific strategies (Chi, 1978; Chi, Feltovich, & Glaser, 1982). As the study by Chi (1978) showed, in knowledge-free tasks, performance differences between young children and college students can be attributed to chronological age. But in knowledge-specific tasks it is knowledge about the particular problem situation, and not age, that can account for differences. Further support is also given by the results of the study by Wason and Johnson-Laird (1972) indicating the importance of the context and its primacy over structural characteristics of problem solving situations. And Carey (1986) stresses the importance of context in understanding all kinds of information, since it allows access to known schemata that will, in turn, provide a framework for understanding.

More recently, however, a third kind of "contextual" knowledge has been identified. Bransford et al. (1986), drawing on a number of studies, report on a kind of "conditionalized knowledge that includes information about the conditions and constraints of its use" (p. 1,081). This knowledge, according to Prawat (1989) is about knowing "when" and "why" to use a procedure, that is, under what circumstances a certain rule is appropriate. But it is not only procedural, since the "if-then" pattern of thinking goes beyond the procedural knowing "how."

Schemata

In the Critique of Pure Reason, Kant (1787/1934) provides arguments for the existence of innate schemata that guide our reasoning process:

> In truth it is not images of objects, but schemata, which lie at the foundation of our pure sensuous conceptions. No image could ever be adequate to our conception of triangles in general. For the generalness of the conception it never could attain to, as this includes under itself all triangles, whether right-angled, acute-angled, etc., whilst the image would always be limited to a single part of this sphere. The schema of the triangle can exist nowhere else than in thought. (Kant, 1787/1934, A141/B180)

In modern literature of cognitive science the word "schemata" is quite ubiquitous and schemata serve as guides or maps in the interpretation of any kind of new knowledge (Anderson, 1985; Rumelhart & Ortony, 1977). These schemata become manifest in reading (Anderson, 1984), human reasoning (Johnson, 1987; Johnson-Laird, 1983), problem solving (Greeno, 1978; Larkin, 1983) and in science learning (Carey, 1986; Driver, 1973, 1991; Driver & Erickson, 1983; Resnick, 1983), and they point towards the holistic mechanism of human understanding (Gardner, 1987).

It was Piaget who first introduced the concept of "scheme" (1970) as a general and goal-defined action that can be generalized by repetition, and which helps people, from infants to mature adults, to interact and thus make sense of the world.

> Whatever is repeatable and generalizable in an action is what I have called a scheme, and I maintain that there is a logic of schemes. Any given scheme in itself does not have a logical component, but schemes can be coordinated with one another, thus implying the general coordination of actions. . . . For example, a scheme can consist of subschemes of subsystems. If I move a stick to move an object, there is within that scheme one subscheme of the relationship between the hand and the stick, a second subscheme of the relationship between the stick and the object, a third subscheme of the relationship between the object and its position in space, etc. (Piaget, 1970, p. 42)

Knowing, according to Piaget (1970), is the assimilation of reality to the existing scheme, and, simultaneously, the accomodation of the schema to reality. According to Kitchener (1986),

> action schemes (e.g., sucking, pulling, turning) are thus pure behavioral dispositions and also practical concepts--or more correctly, the sensorimotor equivalents or precursors of concepts--into which objects are assimilated. (Kitchener, 1986, p. 17)

But the idea of the "whole" as a schema that guides the knowing process is better described by Anderson (1985) who defines it as structure or cluster of knowledge representing an object or event. This generalized knowledge facilitates understanding and making inferences about the world. According to Anderson (1985), schemata are an economical way to store propositional representations about a particular concept, since an immense number of propositions is condensed into a limited number of "slots." These slots are "filled in" by the various attributes of the concept. For example, an immense number of propositions about the concept "house" can be represented through a few slots referring to Structure, Location, Function, and so forth (Anderson, 1985). However, a schema can take the form of network of concepts, like a concept map.

Johnson (1987) also sees schemata as structures for organizing our experiences in order to comprehend the world. However, he argues that schemata "fall between abstract propositional structures . . . and particular concrete images" (p. 29), and are derived from bodily experiences. For example, our bodies as three-dimensional containers give rise to a "containment" and an "in-out" schema, while "pushes" and "pulls" help develop "motion-is-in-the-direction-of-force" schemata.

The importance of conceptual schemata has been documented by Gick and Holyoak (1983) who demonstrated that access is considerably facilitated when prior experiences induce the relevant schema. And Bransford and Johnson (1973), in an influential study, showed that, without a schema with which new information can be integrated, people have considerable difficulty in making sense of a passage from a text. All subjects who participated in the study thought that the text was incomprehensible, and they could remember very little of it. However, once the subjects were allowed to look at a picture that provided the context, comprehension became possible. It is apparent that the visual image of the context, as was perceived from the picture, acted as a conceptual schema to which all information from the text was related.

The importance of schemata has been also pointed out by Chi, Feltovich, and Glaser (1982) who studied the differences between experts and novices in problem solving. Whereas the former organize their knowledge in terms of schemata by placing together problems solvable either with Newton's laws or the concept of energy, the latter tend to classify problems according to surface features such as pulleys, pendula, inclined planes and so forth. In addition, it was found that experts' schemata contain more procedural knowledge, with certain conditions for applicability (that is, conditional knowledge), while novices' schemata contain more declarative knowledge about the physical configurations of the problem.

The Direction of Cognition

One of the characteristics of the cognitive perspective is its holistic mechanism (Gardner, 1987). This means that the direction of cognition is from whole to parts, rather than from part to part or from part to whole. Piaget (1971b) stresses the fact that when we perceive a house, we do not see first "the color of a tile, the height of a chimney and the rest, and finally the house," but, instead, we "immediately see the house as gestalt and then analyze it in detail" (p. 65). The word superiority effect testifies to the fact that even letters are perceived more accurately when they are part of a word than when they do not form a word (Kreiger, 1975; Smith & Spoehr, 1974). Although the word superiority effect could be interpreted as a decoding process whereby letters are more easily and more accurately recognized when they are in the context of a word rather than by themselves, it nevertheless provides evidence for the primacy of the whole over the individual parts.

The ideas of "wholes" and "patterns of organization" had been investigated by the early Gestalt Psychologists (Koffka, 1935; Kohler, 1925; Wertheimer, 1945), and their ontological priority has been emphasized by the dialectical perspective (Basseches, 1980), and the theory of Personal Knowledge (Polanyi, 1958, 1959). Both the dialectical perspective and the Theory of Personal Knowledge stress the idea of perceiving the "whole."

Polanyi (1959) equates the knowledge of a comprehensive whole with an understanding which presupposes "an indwelling" (p. 66). It is evident that this notion of "indwelling" implies a personal meaning, which, as Phenix (1964) points out, "is not developed through formal instruction" (p. 196).

> According to the theory of Personal Knowledge, all meaning lies in the comprehension of a set of particulars in terms of a coherent entity--a comprehension which is personal act that can never be replaced by a formal operation. (Polanyi, 1959, p. 49)

The whole-to-parts direction of cognition can be also seen in the idea that understanding begins with the acquisition of general, rather than specific, concepts. According to Ausubel et al. (1978), new knowledge is always subsumed under a given concept or proposition that already exists in the cognitive structure (p. 124). Unless there is a general concept in the cognitive structure, this subsumption will not take place, and the new knowledge will be simply retained as meaningless information. It is obvious from what Ausubel and his collaborators suggest, that the more general an existing concept in the cognitive structure is, the better or easier the subsumption, and therefore the better the understanding. "Students fail to understand because most inclusive concepts have not been presented first" (p. 153). That is why they are very critical of the idea that simple concepts should precede more complex and general ones.

> Children first form intuitive concepts of work from their experience with carrying toys up to their room, recognizing in time that carrying more weight to higher levels takes more work. As children gradually recognize the scalar values for weight and height and learn how to perform simple arithmetic operations on scalar quantities their concept of work can subsume new meanings and become differentiated to include the mathematical characterization that forces (or weights) and distances combine to define the physical quantity of work. . . . Assimilation theory stresses the importance of superordinate concepts for facilitation of new learning through subsumption of new, relevant information or concepts. When this does not occur, students of physics may learn to perform algebraic manipulation necessary for solving problems using the algorithm W=F*d and still not recognize that it takes more work to move a Cadillac up a mountain than it does to move a Toyota. (Ausubel et al., 1978, p. 362)

<u>The Expectations of the Knower</u>

Munz (1985), arguing from an epistemological point of view, says that humans possess expectations which are responsible for our growth of knowledge. Without the expectation to hear and see objects and events we would not be able to recognize second objects and events since they are different from each other in each particular (p. 27). Although, for example, every man is clearly different and distinguisable from another, we recognize each one of them as a man. The same holds true for a triangle and a sunset. Polanyi (1969, p. 167) interprets this expectation as a process of "tacit knowing," and, as it becomes evident, solves, or rather better justifies, Plato's argument for the existence of eternal universal ideas.

> A universal concept usually anticipates the occurence of further instances of itself in the future, and if the concept is true, it will validly subsume these

> future instances in spite of the fact that they unpredictably differ in every particular from all the instances subsumed in the past. (Polanyi, 1969, pp. 170-171)

Polanyi (1969) further argues that our expectations represent not only our ability to recognize problems, but also our innate capacity to know and differentiate between good and bad problems, and to pursue them successfully.

> A problem designates a gap within a constellation of clues pointing towards something unknown. If we hold a problem to be a good one, we also imply that this unknown can yet be discovered by our own efforts, and that this would be worth these efforts. (Polanyi, 1969, p. 171)

From a pedagogical point of view according to Driver and Bell (1986), the expectation to form meaning is a necessary condition for understanding. It is quite apparent, however, that this expectation is not just a kind of motivation that will act as a prerequisite for "putting all knowledge in the head." It is rather a commitment on the part of the person who wants to understand (Woods & Barrow, 1975). The expectations to understand is part of what Carey (1986) calls "the cognitive rationale" since it requires people to actively construct meaning. This has also been pointed out by Wheatley (1991, p. 11) who says that "we cannot transmit meaning but must construct it for ourselves" since "we give meaning to what someone says by first anticipating what they will say."

The expectation to form meaning is at the very heart of the constructivist perspective. Since, according to

Glasersfeld (1989, p. 134), "a language user's meanings cannot be anything but subjective constructs derived from the speaker's individual experiences," human communication becomes possible only because the "receiver says and does nothing that contravenes the speaker's expectations." Bruner (1986) also remarks that "looking and listening are shaped by expectancy, stance, and intention" (p. 110).

The Emotions of the Knower

The correlation between affect and academic achievement is well documented by a recent study (Rennie & Punch, 1991). Yet it was very unfortunate that the work on the Taxonomy of Educational Objectives (Bloom, 1956) separated, quite inadvertently, the domains of the human brain. Regardeless of whether or not the initial intention was otherwise, understanding was viewed as something separate from emotions and feelings; the cognitive domain was different from the affective domain. And although the importance of motivation and feelings had not been dismissed, they were both seen as prerequisites or starters, rather than integral parts, of the process of understanding: one must be first motivated and then understand. This, of course, can, and very often does happen, but the important point which, unfortunately, was missed is that both feelings and understanding go together. This is the reason why accomodation and conceptual change are difficult to occur, and students hold on to their beliefs even after several years of instruction.

The idea that our emotions play a major role in governing our cognitive functioning seems to be gaining great acceptance among cognitive scientists (Bower, 1981; Deweck, 1986; Norman, 1981). Their findings point towards a cognitive component of motivation and the interrelationship between motivation and cognition, and tend to justify Scheffler (1991) who argues for "cognitive emotions." Ausubel et al. (1978), it should be stressed, had remarked upon the idea that the causal relationship between motivation and understanding is reciprocal rather than unidirectional. Bruner (1963) also saw motivation, particularly that arising from curiosity and interest, as a way to sustain rather than initiate the knowing process. At present there is a changeover, even more recent than the cognitive revolution itself. "Hot Cognition" is a term that is espoused by cognitive scientists, and affect is viewed as internal representations with structural properties, similar to those of schemata (Ortony, Clore, & Lollins, 1988).

The Social Dimension of Knowledge

No doubt cross-cultural studies like those that have been quoted previously provide adequate evidence for the effect of language on the meaning of concepts. However, the construction of meaning is not limited just to semantic factors; instead this construction is the result of the fact that human beings in general interact with one another. As Glasersfeld (1985) argues, "the consideration of Others . .

. is an indispensable requirement of the construction of reality" (p. 99). He also points out that the highest level of reality is achieved only when the cognitive structures of Others are taken into account. The following quotation makes this point quite clear.

> Having attributed the power of spontaneous movement, say, to a lizard, the child who would like to catch one will quickly come to the conclusion that her attempts would be more likely to succeed if, beyond the ability to move, the lizard were also thought of as being able to see and perhaps even to hear. . . . In other words, the child's reality will soon be populated by experiential items to which the child attributes capabilities modelled after those she attributes to herself. Some of these perceiving creatures--especially those with whom the learning and maturing subject frequently has occasion to interact--will require an even more sophisticated model than the lizard. . . . That is to say, other creatures will come to be thought of as possessing cognitive structures and ways of operating that are similar to, but not identical with the subject's own. (Glasersfeld, 1985, p. 98)

Mead (1934) had made the point that giving meaning to any experience becomes possible only within the social process. In fact, Mead argued that it is the social interactions which are responsible for both the appearance of new objects in the field of our experience and the consensus about the existence of objects of common sense.

> The social process, as involving communication, is in a sense responsible for the appearence of new objects in the field of experience of the individual organisms implicated in that process. Organic processes or responses in a sense constitute the objects to which they are responses; that is to say, any given biological organism is in a way responsible for the the existence (in the sense of meanings they have for it) of the objects to which it physiologically and chemically responds. There would, for example, be no food--no edible objects--if there were no organisms

> which could digest it. And similarly, the social process in a sense constitutes the objects to which it responds, or to which it is an adjustment. That is to say, objects are constituted in terms of meanings within the social process of experience. (Mead, 1934, p. 77)

Dewey (1956), in acknowledging the social dimension of knowledge construction, stressed the notion of "community" and asserted that

> every individual has grown up, and always must grow up, in a social medium. His responses grow intelligent, or gain meaning, simply because he lives and acts in a medium of accepted meanings and values. Through social intercourse, through sharing in the activities embodying beliefs, he gradually acquires a mind of his own. The conception of mind as a purely isolated possession of the self is at the very antipodes of the truth. (Dewey, 1956, p. 344)

Vygotsky (1978) shares the same view with Dewey since at the heart of his theory is the idea that all learning is embedded in a social context. The assumption that "processes such as deduction and understanding, evolution of notions about the world, interpretation of physical causality, and mastery of logical forms of thought . . . occur by themselves" is criticized (p. 79). In contrast to the Piagetian child that is busily acting on reality and constructing schemata, and to Kelly's man-scientist who is making hypotheses and constructing models in isolation in order to expain and predict events, students understand because they share and negotiate meanings. Understanding, in this sense, becomes possible because communication creates a common frame of reference. This frame of reference is based upon an "agreement with others about types of objects and experiences which are explicitly context-dependent" (Solomon, 1987, p. 67).

Over the last decade the social dimension of human knowledge has been emphasized by both cognitive scientists and science educators. Norman (1981) explicitly states that "human cognition exists within the context of the person, the society, the culture" (p. 1), and Wheatley (1991) says that, "knowledge is not something people possess in their heads, but rather something people do together" (p. 11). The idea of the "solo child" learning science has also been reconsidered by Bruner (1986), the advocate of the inquiry model, who acknowledges the importance of the social context in the construction of knowledge. Bauersfeld (1988) also stresses the importance of negotiating meanings in a social interaction, and Wheatley (1991), quoting Johnson (1987), accepts that "to know is to understand in a certain manner, a manner which can be shared by others who join with you to form a community of understanding" (p. 10). Solomon (1987), in discussing the social construction of meaning, notes that in an attempt to make sense of the world we integrate a personal "stock of knowledge" resulting from beliefs, talked-over experiences, and hear-say into a socially constructed picture; and through social exchanges, we seek to reconfirm the fact that those people close to us see the world as we do. And as Solomon remarks, "this continual reaffirmation of social notions makes them very durable and resistant to change" (p. 67). At present, there is a strong consensus about "socially situated cognition" that explains how individuals can understand each other despite, the fact that each one of them has constructed knowledge independently in his/her mind (Resnick, 1991).

> According to the strong constructivist assumption, everything an individual knows is personally constructed. But directly experienced events are only part of the basis of that construction. People also build their knowledge structures on the basis of what they are told by others, orally, in writing, in pictures, and in gestures. Our daily lives are filled with instances in which we influence each other's constructive processes by providing information, pointing things out to one another, asking questions, and arguing with and elaborating on each other's ideas. (Resnick, 1991, p. 2)

Social interaction in classroom settings has been investigated by a number of researchers who provide evidence that the interaction taking place within cooperative groups results not only in considerable gains in terms of self esteem, social and cross-cultural relationships, but also in terms of academic achievement (Sharan & Shachar, 1988; Slavin 1988, 1989; Watson, 1991). In fact, cooperative groups that encourage shared understanding lead to higher levels of critical thinking (Sharan & Shachar, 1988; Webb, 1982).

There is a good reason to believe that this critical thinking is the outcome of a dialectical process through which opposing points of view--thesis and antithesis--are resolved. Johnson and Johnson (1988) propose "structured controversy" as a means to negotiating meanings in classroom settings. A controversial topic, they recommend, such as environment and energy, should provide the start of a debate that will in turn allow students with opposing points of view to confront one another until the issue is resolved. Paul (1984) also argues that the disequilibration resulting from conflicting points of view helps develop critical thinking.

There is also reason to believe that students who feel isolated are provided with group support which in turn encourages the development of an environment that allows for opportunities for expressing ideas without the fear of being wrong. However, there seems to be another reason why passive and withdrawn students begin to adopt an active role once they become part of a group. For it could be argued that, although it is the interaction taking place within the group that gives students opportunities to be both teachers and learners at the same time and thus enhance their thinking (Kraft, 1985), it is the relationships formed during the interaction that both provide and sustain meaning in classroom settings. It is probably this meaning that acts as an incentive for thinking and sharing, and therefore responsible for an increase in performance.

Webb (1984) investigated how different gender groupings can affect learning. It was found that, when the groups consisted of an equal number of males and females, the performance of both genders was the same. But when fewer females than males were in the groups, the males appeared to ignore the females, and consequently the performance of the latter decreased. Perret-Clermont (1980) studied the concept of conservation among children of age 5 to 7 years and found that, if a child who did not have the concept of conservation was put together with two conservers there was progress, while a group consisting of two non-conservers and one conserver showed occasional progress. No progress was made if three non-conservers were put in the same group, though non-conservers from the control group made progress.

The social nature of knowledge and the notion that "all the ideas and sentiments which motivate an individual" have not "their origin in him alone" (Mannheim, 1936/1972, p. 2) had been recognized much earlier by both sociologists of knowledge and historians of science. Weber (1949), in his interpretive epistemology, argued that concepts are constructed and reconstructed by individuals in their attempt to make sense of the world.

> Concept construction depends on the setting of the problem, and the latter varies with the content of the culture. The history of the social sciences is and remains a continuous process passing from the attempt to order reality analytically through the construction of concepts . . . and the reformulation anew of concepts on the foundations thus transformed. (Weber, 1949, pp. 105-107)

Mannheim (1936/1972) further stated that "it is incorrect to insist that the single individual thinks" and would be more correct to say that "he participates in thinking further what other men have thought before him" (p. 3). Barnes

(1977) also discussed in detail how the social environment influences the generation and maintenance of knowledge.

> Knowledge is not produced by passively perceiving individuals, but by interacting social groups engaged in particular activities. And it is evaluated communally, and not by isolated individual judgements . . . its maintenance is not just a matter of how well it relates to reality, but also of how it relates to the objectives and interests of a society. (Barnes, 1977, p. 2)

Further evidence is provided by Munz (1985) and Kuhn (1970). The former takes the case of Leonardo Da Vinci to show how disorder and social unrest gave him the liberty to dissect corpses, and thus advance medical knowledge. And the latter argued that scientific knowledge is a social construction, and, far from being objectively true, it is seen as what the community of scientists have decided to accept as true. Kuhn in actual fact, along with Toulmin (1972), argued that science must be understood as a social activity which develops its own rules of practice. They made clear that observations are theory-laden, and therefore they are not "given" but are profoundly shaped by the scientists' preconceptions and theoretical notions.

From a pedagogical point of view the idea that cognitive disequilibration and accomodation imply not just an action on reality but an experience within a social context is epitomized by Solomon (1987) who states:

> Social interaction, whether in the general culture, the peer group, or even, in its most tenuous form, via relationship with a television character, is not just an additional avenue for learning. Both sociological theory and classroom evidence suggest that in

> socially acquired knowledge exchange of meaning and consensus take the place of logical testing, and typification by context replaces abstraction and conceptualization. (Solomon, 1987, p. 78)

In giving due credit to the emotional attachment resulting from social interaction, Berger and Luckmann (1967) also stressed that "there is good reason to believe that without such emotional attachment to significant others the learning process would be difficult, if not impossible" (p. 151).

In discussing the social dimension of knowledge, it should be pointed out that an intuitive type of personal knowledge (Polanyi, 1958, 1959) as well as schemata constructed through sensorimotor experiences at an early age (Johnson, 1987) do occur. However, accepting the inevitability of social exchanges, the interactive element that exists in classroom and other social settings will be responsible for the reaffirmation, modification, and even complete abandonment of those personally generated ideas. Even if one goes contra Mannheim, and argues that thinking is a subjective activity, the notion of "community of understanding," as was put by Johnson (1987, p. 206), and the "rationale for considering Others" (Glasersfeld, 1985, p. 99) are at the very heart of the problem of human understanding.

The Challenge for Constructivism

Accepting the view that reality is constructed in the mind of each individual in his or her attempt to make sense of the world, it is no surprise why children, and even mature adults, hold ideas which are at variance with those of the scientists. It is also no surprise why most of the interest of science educators is in the area of science, particularly in mechanics.

Motion and forces are an indispensable part of our everyday life, and particularly of the life of children. Physical experience is their primary source of knowledge that starts with grasping a hand, pulling and pushing chairs, keeping their balance, and continues through life with throwing different objects with some expectation as to the path they will take, with walking, jumping, lifting, and running. However, these bodily experiences give rise to the construction of schemata that act as organizers for the subsumption of all of our subsequent concepts and experiences. For as Johnson (1987) argues, all abstract concepts and principles stem from bodily experiences through metaphorical projections into abstract domains. Even psychological states, arguments, moral rights, and mathematical operations are metaphorically structured as physical events. Unfortunately though these conceptual schemata are different from those employed by the scientists, and even more unfortunately, these schemata do make sense. And this is the real challenge in the area of conceptual understanding: to identify the "wrong ideas that sound right" to the students, as well as possible factors that might account for their development, and then devise ways to change them (Brown & Clement, 1989; Dykstra et al., 1992; Gorsky & Finegold, 1992).

Part 4: Studies On Conceptual Understanding

Studies on how students understand science concepts can be divided into two major categories. In the first category belong studies that identify whatever ideas students have in their mind without any attempt to compare those ideas to the scientific ones; these studies are called ideographic. In the second category belong studies that deliberately compare students' ideas with the scientific ones; these studies are called nomothetic (Driver & Easley, 1978).

Studies conducted by Piaget and his collaborators could be described as ideographic, although, as Driver and Easley (1978) point out, it is difficult to make a sharp distinction between the two. Phenomenographic studies (Bowden et al., 1992; Marton, 1986) that identify categories or patterns of student's thinking could be also called ideographic. The majority of the studies, however, particularly with high school and university students, should be considered nomothetic, since their primary goal is to identify alternative (other than scientific) conceptions, and then devise ways to change them.

The Contribution of Jean Piaget

The study of conceptual understanding has its origins in Piaget's work in Geneva in the 1930s, where he studied the concepts of time, space, speed, movement, and causality

(Piaget, 1971b, 1971c, 1971d). His work was promoted by a number of questions suggested by Einstein whom he had met at an international symposium on philosophy and psychology at Davos, Switzerland, as Piaget himself reports (Piaget, 1970). The most important findings of his study of the concept of time (Piaget, 1971d) are: (a) Children confuse the concept of time with speed and distance, (b) the concept of speed is more fundamental than the concept of time, and (c) time is the co-ordination of motions at different speeds. Particular attention, however, deserve his investigations of the intuitive concept of speed. Piaget (1971e, p. 136) grouped his tasks of two moving objects into three major categories:

1. The starting and stopping points alone are visible; the paths are unequal in length, run parallel and in the same direction, and the objects start together and also stop together at the end.

2. Both paths are altogether visible; the paths are unequal in length, and the starting and stopping points are the same.

3. The objects are traveling side by side on two concentric tracks of unequal sizes, and visible throughout.

The findings of Piaget's research were very interesting and can be summarized as follows:

1. Movement is assigned a cause.

2. All movement has a goal (finalism).

3. All movement implies an inherent power (dynamism).

4. The speed of movement is judged by the points of arrival rather than by the time it takes and the distance.

5. Overtaking is equated with "going faster."

However, the most significant result of Piaget's study was the parallel which was identified between the children's intuitive ideas and the ideas of Aristotle's physics. The significance of Piaget's studies could be summarized in one short paragraph:

> All movement tends towards a goal and implies an inherent vital or creative power. Hence a number of analogies with Aristotle's physics, in particular the hypothetical need for two motive forces, one internal and the other external, to explain movement like that of clouds or river water. (Piaget, 1971e, p. ix)

<u>New International Interest in Conceptual Understanding</u>

In addition to Piaget's work in Geneva, other researchers came to recognize the value of what became known as clinical interview as a diagnostic device for evaluating students' understanding. In the early studies on conceptual understanding Piaget's work was replicated. In England King (1961) asked children of ages four to early adolescence to give their explanation of natural phenomena, ranging from the origin of night and the movement of the clouds to objects they were able to manipulate such as bicycles or different things that float or sink in water. The findings just confirmed what Piaget had found. That in passing from an initial state of egocentricism as very young children to objectivity as young adults, children's explanations pass through a pre-causal phase: a phase were explanations are teleological and animistic.

Results of similar studies indicated that animism and precausal forms of thinking can persist into adolescence (Laurendau & Pinard, 1962). Nussbaum and Novak (1976), in a pioneering study at Cornell University, questioned 7- to 14-year-old students using drawings and models. They studied how the children's concept of the earth develops, and several conceptual frameworks were identified. Children's notions about the earth evolve from a flat-earth notion, through a notion of the earth as a hollow sphere with life existing on a platform at the bottom, to a spherical earth with gravity. The value of this study was not so much that it could establish norms of conceptual development in learning science, but that it raised the awareness of the possible alternative perspectives that students may bring to the classrooom with them and influence effective communication. The study also gave evidence to what Ausubel (1968) was claiming at the time: that preconceptions are the most important factor of the learning process, and they are likely to persist despite instruction.

It was in the light of these studies that a new international interest in conceptual understanding was shown worldwide. The area of Newtonian mechanics received special attention. However, these new studies began to investigate, not only children's intuitive ideas, but also alternative conceptions of high school and university students. What follows are studies on preconceptions in the area of force and motion.

Preconceptions and Conceptual Understanding in Mechanics

In an influential study on dynamics, Viennot (1979) was the first to raise the awareness that university students entertain the same ideas as young children, and also remark that these ideas can exist in the minds of students without any conflict with what they are actually taught. Her central claim was that the student's concept of force has two distinct versions or models, each called upon in different contexts. The first model she called "force of interaction" representing a force that satisfies the equation $F = ma$. The force of interaction is a function of position and is used in contexts in which a local analysis of the problem situation is required, usually problems involving static situations, or when the the force acts in the same direction as the motion. In this context students speak of "the force acting on the body." The other model she called "supply of force" and it is used whem motion is made obvious in the statement of the problem, and particularly when the motion is in the opposite direction to the resultant forces. In this particular context, students speak of "the force of the body" in order to account for the motion of the body.

Viennot (1979) stressed the fact that major teaching effort is needed if we want to replace the students' preconceptions. She remarked that "teaching of the Newtonian scheme will only be effective when students are led to look at the discrepancies between it and their spontaneous ideas" (p. 213).

However, Viennot's study was very significant because she found that the preconceptions held by high school and university students are "closer to the impetus theory than to Aristotle." Piaget (1971d), in studying young children's ideas about the motion of clouds and river water, had found that children adopt the Aristotelian schema, thus employing one inherent and one external force. This shift in the paradigms generated an interest in mechanics on both sides of the Atlantic, and studies undertaken by Watts and Zylbersztajn (1981), Clement (1982), McCloskey (1983), Halloun and Hestenes (1985b), and Lie (1985) provided evidence for an impetus theory of motion in the thinking of many students.

Clement (1982) argued that the students' intuitive ideas represent an integrated and coherent theory which has parallels with the pre-Galilean impetus theory of motion. He suggested that it is the coherence of this impetus theory which contributes to its stability. Central to the impetus theory that was first propounded by the Greek scholar Yannis Philoponous in the 6th century, and was fully developed by the French philosopher Jean Buridan in the 14th century, is the notion that a moving object must have an inherent motive power or force. This internal power or force is dissipated as the object moves, and when it is all used up the object will either come to a stop, or start moving downwards due to gravity (Butterfield, 1957; Cohen, 1985; Crombie, 1963). This theory was a correction to the Aristotelian paradigm because it could better explain the motion of a projectile. Aristotle had been obliged to accept that the air must be continually pushing the arrow after the latter leaves the bow. The impetus theory circumvented this difficulty by assuming something inherent in the body (Butterfield, 1957). However, it shared with Aristotle's theory the idea that every motion must have a cause, and, therefore, the idea that motion in the absence of forces is impossible. The impetus theory differs substantially from the Newtonian paradigm in the sense that it makes a distinction between motion and rest; moving objects have impetus while objects at rest do not.

In Newtonian mechanics moving bodies have momentum, which, however, is not inherent in the bodies themselves. Furthermore, this momentum is not the cause of motion or an agent that sustains it, but simply "a quantity employed to describe motion" (McCloskey, 1983, p. 125), and it can in fact be in a direction opposite to, or generally different from, that of the force. For example in the case of a ball moving straight up in the air the acting force, that is the weight, is downward, while the momentum is in the upward direction. In addition, the impetus of a body is viewed in an absolute sense, in sharp contrast to the momentum, which, like velocity, is always defined relative to frame of reference.

Also, according to the impetus theory there is no fundamental distinction between linear and circular motion; both forms of motion require a certain amount of impetus. In Newtonian mechanics though, it is only circular motion that always requires the action of force. Motion in straight line though can exist even in the absence of forces if the speed is constant (McCloskey, 1983). It is probably this conceptual difficulty, namely, the association of uniform motion with zero force that makes students develop the conceptual schema "Motion implies a Force," and be, according to (Cohen, 1985), in the same position as the scientists of the past. However, not all students use the impetus theory in their thinking. Halloun and Hestenes (1985b) found that 18% of a sample of 478 university physics students were predominantly Aristotelian. In addition, they noticed that the conceptual systems employed by the students "have much less internal coherence than the Aristotelian and Impetus systems" and could be described "as bundles of loosely related and sometimes inconsistent concepts" (p. 1,058). In regard to Newton's first and second laws, for example, although 84% of the sample held the Newtonian conception that a free particle moves in straight line, only 30% believed that the speed of such a particle remains constant, and only 15% thought that under a constant force a particle has a constant acceleration.

In the 1980s several studies on how students understand concepts of force and motion were undertaken, and several preconceptions were identified. Although these preconceptions are misinterpretations of Newton's Laws of Motion, and, therefore, they are interrelated, a detailed breakdown by reference to the particular investigators would better show the patterns that students employ in their reasoning.

<u>The direction of the resultant force is the same as the direction of motion</u>. This preconception is probably a subsumption of the more general schema namely "Motion implies a Force," and is reminiscent of the Aristotelian belief of an inherent internal force as well of the pre-Galilean impetus theory (McCloskey, 1983). Several studies undertaken with secondary school as well as with university students have shown that the idea of a force acting in the direction of motion is very common.

In a survey carried out by Watts and Zylbersztajn (1981), junior-high school students were given a questionnaire with coded answers associated with the forces acting on a cannon ball at different points of the trajectory. As Watts and Zylbersztajn report, 85% of the students identified a force in the direction of the ball's motion (Figure 2).

It is quite interesting to note that the researchers conducted interviews with the physics teachers, in which the latter were asked to predict the percentage of students who would respond correctly to the questionnaire tasks. The predictions, however, were not good enough, since the percentage of the correct answers was considerably lower than what the teachers had expected. For this reason, the researchers recommended that any teaching strategy, in order to be effective, should include:

1. Awareness on the part of the teacher of the existence of children's prior conceptions.

2. Knowledge of some of the forms that these conceptual frameworks can take.

3. Utilization of these conceptual frameworks as the starting point of the teaching-learning process.

Boeha (1990) replicated the study with 12th-grade high school students in Nigeria. He used semi-structured interviews that probed the understanding of the concept of force in the context of a moving softball after it was hit. Boeha (1990) reports identical results with those of Watts and Zylbersztajn (1981), since the majority of students thought that when the softball is hit a force is imparted that accompanies it during its flight, and which gets used up. However, Boeha (1990) calls that kind of thinking Aristotelian, although it resembles more to the impetus theory as has been noted by McCloskey (1983) and Viennot (1979).

Clement (1982) reports how university students in their laboratory write-ups about the motion of a simple pendulum identified a force in the direction of the motion of the bob, suggesting that if there were no such a force the pendulum could never move up to the top of its swing (Figure 3). Most students who participated in the study, as Clement (1982) reports, identified a force in the direction of motion regardless of whether or not the pendulum was swinging up or down.

Similar results with the motion of the pendulum were obtained by Sjoberg and Lie (1981) as reported by McDermott (1984). Sjoberg and Lie (1981) conducted a study with Norwegian high school and first year university students. They were among the first to stress the importance of preconceptions for the teaching process.

In another study, as reported by Roper (1985), 31% of a sample of university science and engineering students at the University of Leeds, England, opted for a force in the direction of motion of a ball thrown vertically upwards. When asked, in a paper-and-pencil test, to insert the force(s) on the ball, students identified an upward force when the ball was going up, a downward force when it was

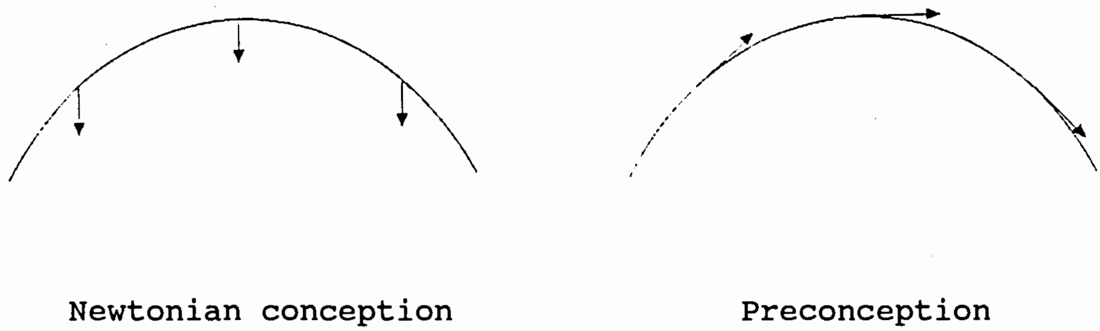


Figure 2. Force Acting on Projectile.

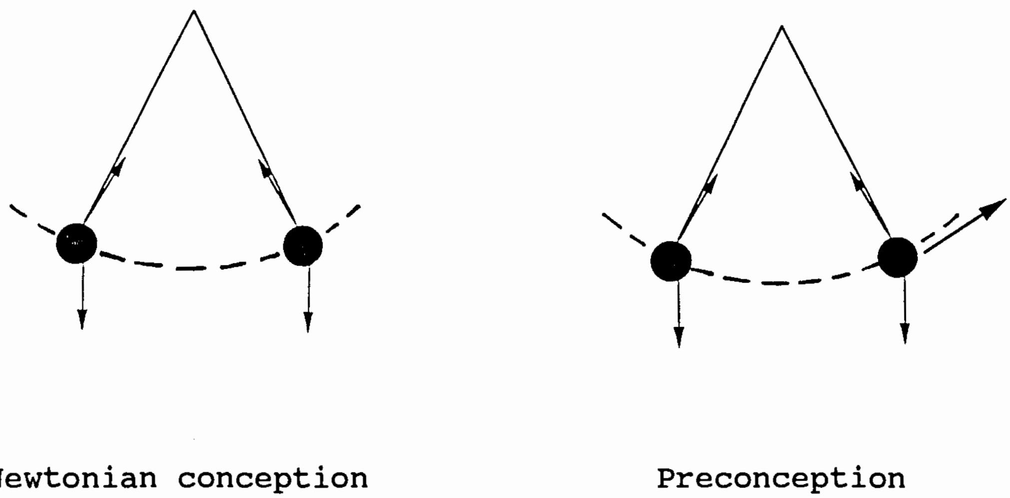


Figure 3. Forces Acting on Swinging Pendulum.

coming down, and no force when the ball had reached the maximum height on its trajectory. Clement (1982) also illustrates the same point, since 72% of a sample of 150 university engineering students at the end of their physics course, predicted an upward force from the hand that must be greater than the downward force of gravity in the case of a tossed coin. The students explained their answer by suggesting that the upward force must be greater, otherwise the coin would be moving down. It is apparent students associated the resultant of the two forces with the motion of the coin.

Clement (1982) also reports on a task that asked students to predict the path of a spaceship, before, during, and after the firing of its engine. The results reveal that the initial sideways motion of the spaceship in a straight line implied a force, which was combined with the force produced by the engine to give a resultant straight line motion in the direction of the resultant force. As soon as the engine is off, the original straight line motion is followed once again (Figure 4). It is quite interesting to note that only 9% of a sample of 150 first year engineering students correctly combined the accelerated motion due to the firing of the engine with the initial straight line motion to produce a parabolic motion, and then a straight line motion at constant velocity according to Newton's first law.

If there is no force there will be no motion. This is exactly the opposite of the above preconception. McCloskey (1983) carried out a study that probed college students' "knowledge-in-action". He asked them to release a ball from their hand as they were moving across the floor in order to hit a target. As he reports, only 45% of the students knew that the ball would travel forward as it fell, while 49% thought that the ball would fall straight down. These students released the ball when they were directly over the target, thus suggesting that they were either neglecting the horizontal component of the velocity of the ball, or assuming that this component was zero as soon as it leaves their hand (Figure 5). The rest 6% thought that the ball would move backwards. These students released the ball after they reached the target.

Motion takes place in the direction of the applied force. In another study, Di Sessa (1982) presented elementary school students with an object on a screen. The object obeyed Newton's laws of motion (it remained at rest or moved in a straight line if no force acted on it), and could be given a force in the form of a kick. Most students ignored the initial velocity of the object, when they were asked to hit the target; they applied the force in the direction of the target.

Motion in the direction of the applied force can be also seen in the case of a spaceship traveling in outer

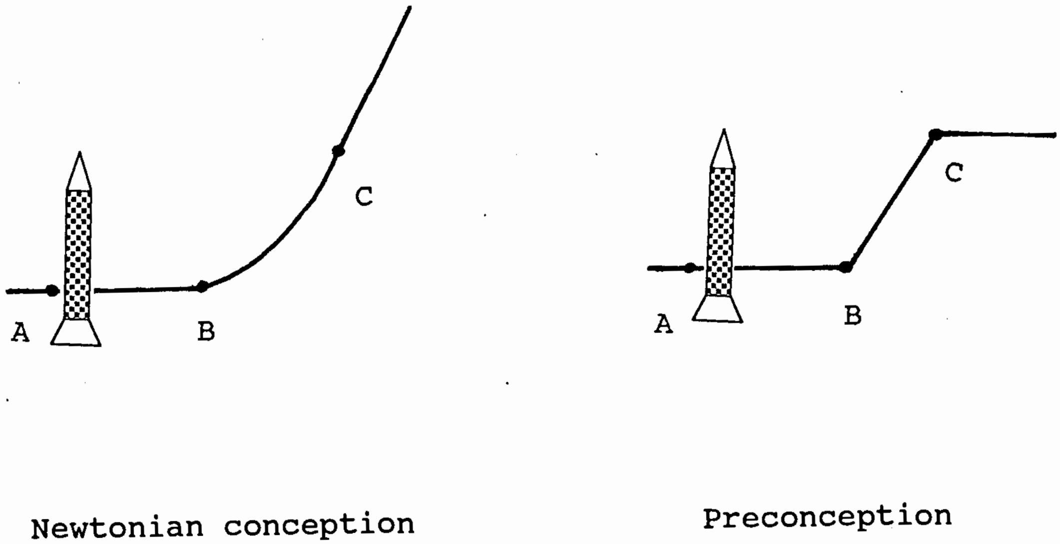


Figure 4. Path of Spaceship Coasting in Space After its Engine is Fired from B to C.

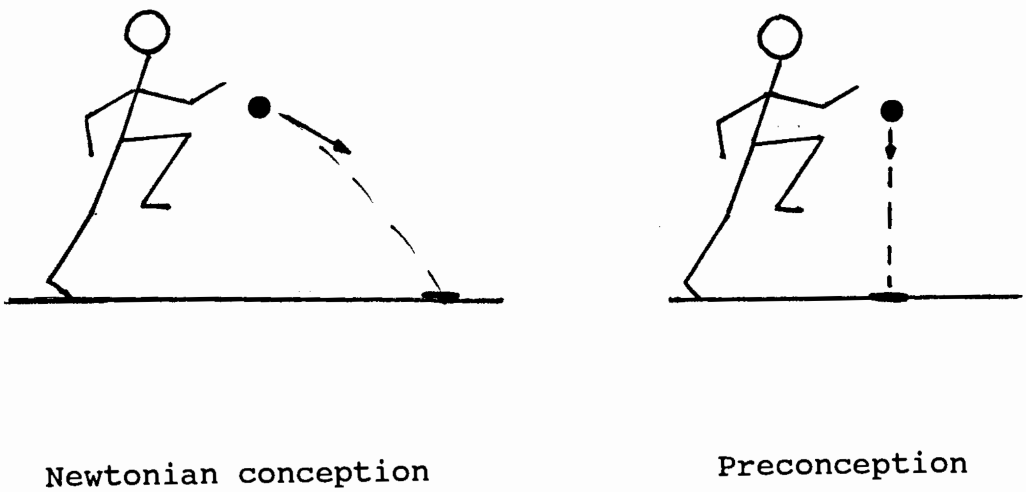


Figure 5. Hitting Target on Floor with Ball Dropped by Running Person.

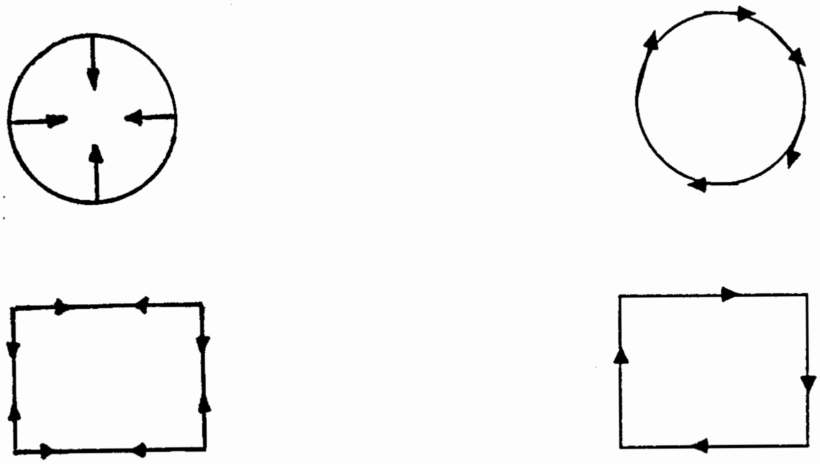
space and propelled by impulse rockets. White (1983) gave series of pencil and paper tasks in an interview mode to a sample of 40 sixteen year old secondary school students. As she reports, when the students were asked to find how they could get the spaceship to fly in a circular and then a square path, they opted for a force in the direction of motion, 70% in the case of the circular path, and 22.5% in the case of the square path (Figure 6). Equally interesting was the fact that 80% of the sample correctly applied the first law of motion and predicted constant eternal motion if the impulse engine of the spaceship were fired once. White noted that students were not consistent in their responses, thus contradicting the argument about an integrated and coherent theory of motion, as reported by Clement (1982).

Force varies with velocity. This is a very widespread preconception since everyday experience suggests that the greater the force the greater the speed. Thus one must apply greater force if one's bicycle is to move with greater speed, and the harder one pushes an object the higher its speed. Viennot (1979), in a study with French, Belgian, and British last year secondary school and university students, confirmed just that.

Viennot presented the students with a number of paper and pencil questions including a question about six juggler's ball, all at the same height above the ground, but at different points on their trajectories, and a question about a system of three identical masses oscillating on the ends of vertical strings (Figures 7 and 8). The students were asked to predict whether the forces on all the balls and the springs were identical. The results indicated that, even at the university level more than half of the students tend to associate force with velocity, assuming that, since the velocities are different, the forces must be different too.

In the problem with the springs, although it was explicitly stated in the test that the force (tension) in a spring is proportional to the elognation, students encountered tremendous conceptual difficulty in reasoning that a mass with non-zero velocity passing through its equilibrium position is not acted upon by a force.

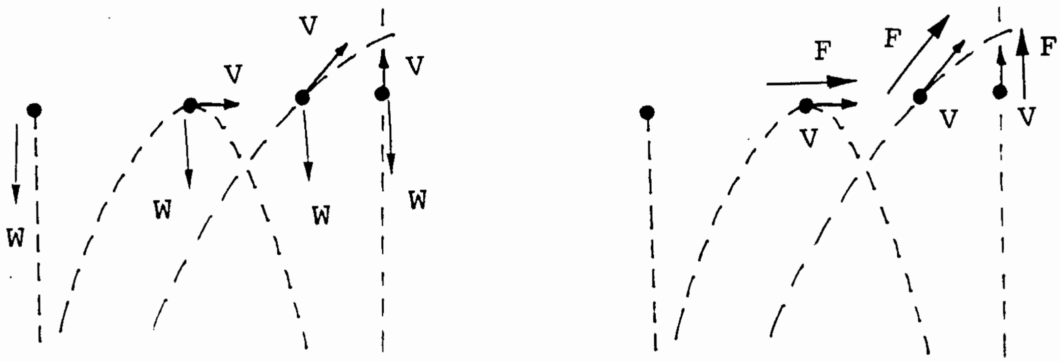
Roper's study (1985) also indicated a similar preconception since students thought that at the highest point of the vertical trajectory of a ball the force must be zero. Although in this particular problem the preconception "force-acts-in-the-direction-of-motion" can give a plausible explanation, as with Clement's (1982) tossed coin problem, the idea that the ball will finally reach a point at which its velocity will become zero makes one suspect that the Aristotelian theory that views force as being proportional to velocity is also employed in students' thinking (Figure 9).



Newtonian conception

Preconception

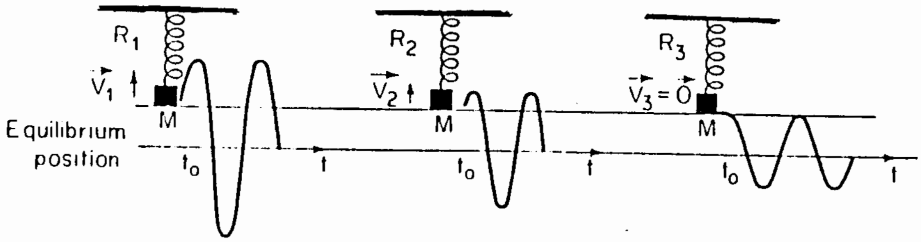
Figure 6. Forces on Spaceship Traveling in Circular and Square Path.



Newtonian Conception

Preconception

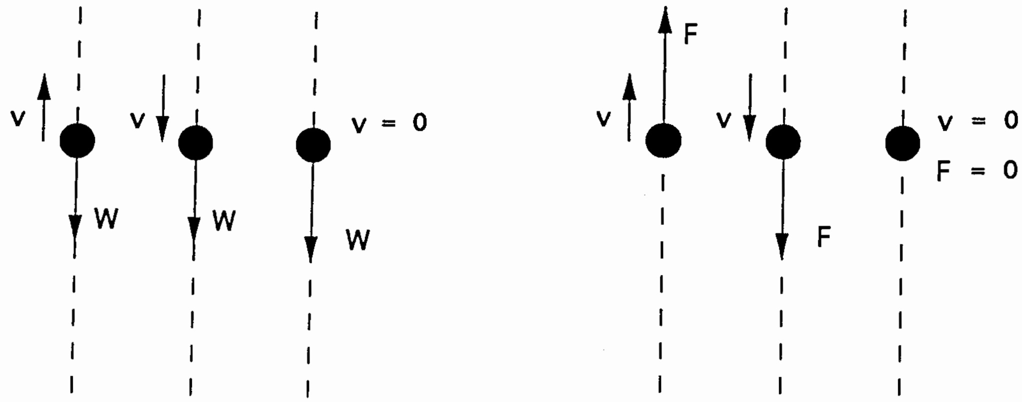
Figure 7. Forces on Balls in Different Trajectories.



$F1 = F2 = F3$ $\qquad\qquad$ $F1 > F2 > F3$

Newtonian conception $\qquad\qquad$ Preconception

Figure 8. Forces on Oscillating Masses in Identical Positions but with Different Velocities.



Newtonian conception $\qquad\qquad$ Preconception

Figure 9. Forces on Ball Moving Straight Up and Down in Air in three Different Positions.

Additional evidence for this preconception is provided by Halloun and Hestenes (1985a, 1985b). In an attempt to survey naive concepts about motion in a group of 478 university physics students, they administered a diagnostic pre-test and a post-test at the beginning and end of the semester respectively. They found that many students believed (66% on the pre-test and 44% on the post-test) that under a constant force a body moves with constant velocity, although only 2% maintained this belief consistently.

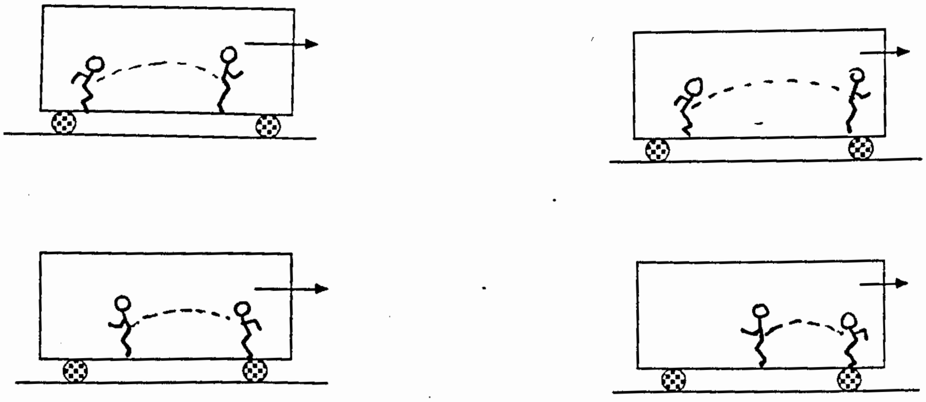
Continuous force is required to maintain motion. This preconception is another manifestion of the more general scheme "Motion implies a Force", and derives from personal experience with pushing and pulling objects. According to McDermott (1984), when university physics students were asked to make a puck on an air table move in a straight line with a constant speed by using blasts from an air blower, their first attempt was to apply continuous blasts. This clearly shows how the students' experience of a body that stops moving once they stop pushing or pulling it influences their reasoning process. A similar preconception among university students has been also found by Jira, McCloskey, and Green (1981). Halloun and Hestenes (1985a) also report that 47% of the students on the pre-test and 20% of them on the post-test expressed the idea that under no net force a body must slow down.

Once a body leaves its frame of reference its motion becomes absolute. This preconception is not surprising if one takes into account the fact that in daily life there is always an absolute frame of reference (i.e., the ground), and that we all share the common sense Aristotelian belief that rest is different from motion. This is what a study by Lie (1985) reports. The idea of "meeting the movement" was very common in two cases. In the first one, students predicted that a broad jump inside a train and in the direction of the train's motion would be longer than a jump in the opposite direction (Figure 10). And in the second case, their prediction was identical: two airplanes that take off from the same place on the equator and fly in opposite directions will complete their trip around the earth in different time intervals. The plane traveling due west will arrive first because it is moving towards the place from which it took off.

Use of absolute frames of reference. It is evident that, in the examples that were discussed above, absolute frames of reference were used. In the case of the train, motion becomes relative in relation to the ground, and in the case of the earth, motion becomes absolute in relation to space. This preference for absolute frames of reference has been documented by Aguirre and Erickson (1983) and Aguirre (1988) who studied high school students' conceptions of the vector characteristics of velocity and displacement.

The tasks that they used were simulated situations in which the subjects were standing on a bridge watching a river boat crossing the river, and on the shores of a lake trying to locate fishing spots. From the clinical interviews it became evident that the students always tried to locate a fixed position on the ground. However, several fixed positions were selected at the same time, thus suggesting that they (students) had difficulty in selecting a standard frame of reference. In addition, it was found that the speed and the path of an object were absolute in the the sense that they were viewed as intrinsic properties of the objects themselves and independent of any frame of reference. These "intrinsic speed" and "intrinsic path" properties of moving objects reconfirm the findings of Saltiel and Malgrange (1980).

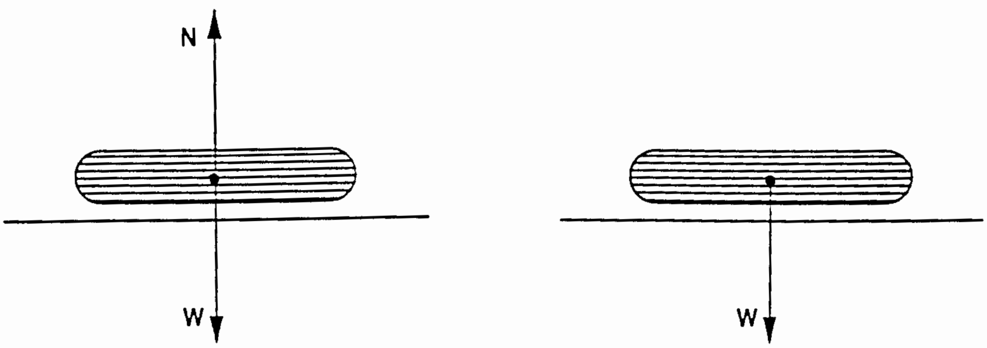
Stationary objects cannot exert forces. Driver (1973) spent several months observing junior-high school students in the laboratory as they were conducting experiments. The idea that a table or a chair cannot exert an upward force when there was no motion was very common. Minstrell (1982) also reports that 50% of his high school students did not believe that an upward force can be exerted on a book by a table. As Minstrell (1982) reports, 50% of his students did believe that the only force acting the book is its own weight (Figure 11). Identical findings have also been reported more recently by Brown and Clements (1987).



Newtonian conception

Preconception

Figure 10. Jumping Inside Moving Train.



Newtonian Conception

Preconception

Figure 11. Forces on a Book Resting on a Table.

Terry, Jones and Hurford (1985) studied the conceptual understanding of forces and equilibrium with children who were at the mid-point of years three, four, and five in their study of physics. Each pupil was presented with a drawing of a box resting on a table and was then asked to explain what kept the box at rest. The researchers report that 95% of the pupils in the year three group asserted that it was not necessary for the table to exert a force on the box. When this response was discussed further, it was found that pupils had considerable difficulty in accepting that inanimate objects like a table can exert a force. However, only 25% and 54% of the other two groups could correctly explain the equilibrium of the box.

Motion is different from rest. Whitaker (1983) replicated one of Galileo's famous thought experiments. In this particular thought experiment, Salviati, the voice of Galileo, is trying to change the belief of Simplicio, an Aristotelian advocate, that a bolt dropped from the top of the mast of a moving ship will not land at a point that is behind, but instead, at the foot of the mast as if the ship were at rest.

As Whitaker reports, many university physics students believed that a bolt hanging loose from the ceiling of a uniformly moving train will not pass through a hole that is on the floor and directly under the bolt. For the students, motion and rest were fundamentally inequivalent (Figure 12).

Velocity is the same as position. Trowbridge and McDermott (1980), in a replication of Piaget's tasks, found that university students confused velocity with position. In observing the motion of two balls moving on different but parallel tracks (one ball with constant velocity on a horizontal track, and the other with an initial velocity greater than the first's ball velocity), they tried to identify the instant of passing in order to judge whether the velocities were equal. They thought that the velocities are the same when the positions are the same. And they also associated the idea of being ahead with having greater speed. As the researchers report, the students employed perception in their thinking, without any attempt to think of velocity as rate of change of displacement. The same results were obtained in a follow-up study with acceleration. Again students confused position and acceleration (Trowbridge & McDermott, 1981).

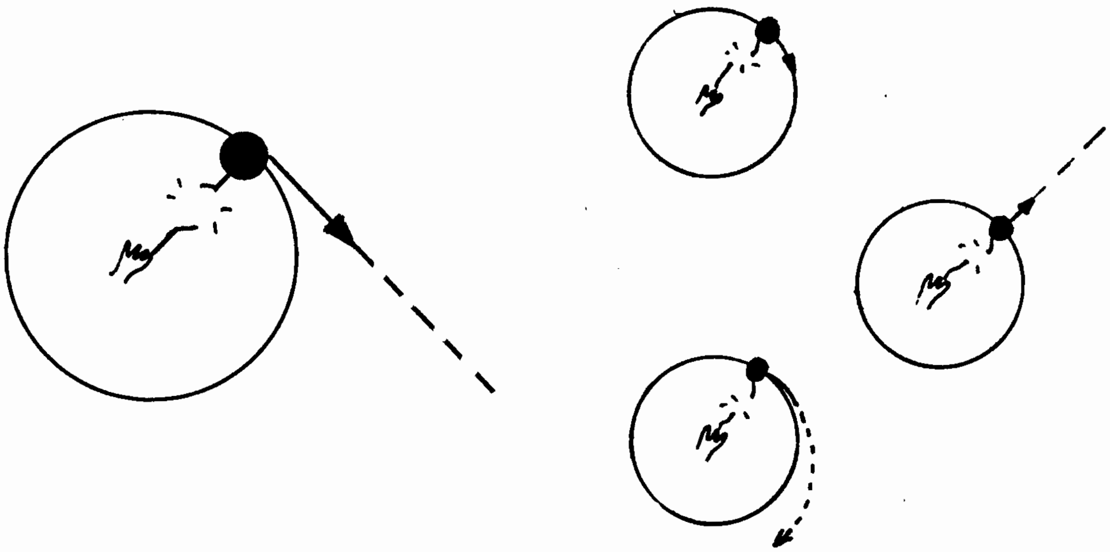
Curvilinear motion in the absence of forces. As Lie (1985), McCloskey, Caramazza and Green (1980), and McCloskey (1983) report, impetus ideas that make students believe that moving objects "remember" their previous motion are widespread among secondary school and university students. For example, a stone tied to the end of a rope and circling around will not follow a straight line path in the direction of the tangent once the rope breaks, but a curvilinear path or a path along the same circle as before (Figure 13). What is very interesting, however, is that in the task of an object moving inside a tube (Figure 14), the longer the object is in the curved tube the more curved its motion will be after it leaves the tube (McCloskey, 1980). In addition, there were differences in the percentage of students who predicted a straight line path. These differences can be attributed either to the time spent inside the curved tube or to the degree of curvature. Lie (1985) reports similar findings, but not as frequent, with the case of a ball that leaves a spiral track. Students with "impetus" beliefs" thought that the path will continue to be spiral.

<u>Preconceptions about Action-Reaction</u>. The preconceptions about Action and Reaction are held both in static and dynamic situations. Roper (1985) and Watts and Zylberstajn (1981) investigated static situations, while Maloney (1984) and Brown (1989) focused on dynamic ones.

Roper (1985) reports how university students confuse the normal reaction from a surface with the reaction to the weight. Students tend to see the weight as Action, and the normal reaction from the table as the Reaction (Figure 15). Watts and Zylberztajn (1981) also report that junior-high school students failed to identify action-reaction correctly in the tug-of-war game. They thought that the winning team must exert a greater force on the rope (Figure 16). It is rather apparent that the movement of the losing team involved

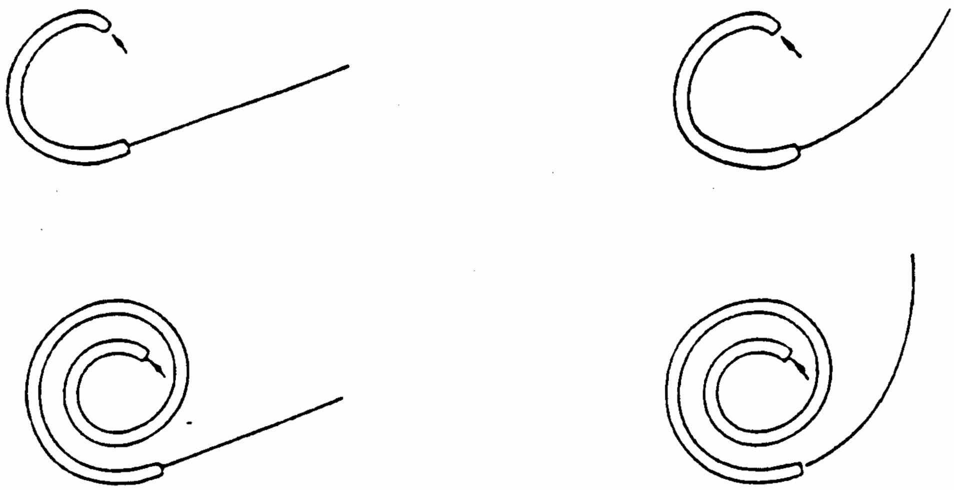
Newtonian conception Preconception

Figure 12. Bolt Falling from Roof of Moving Train.



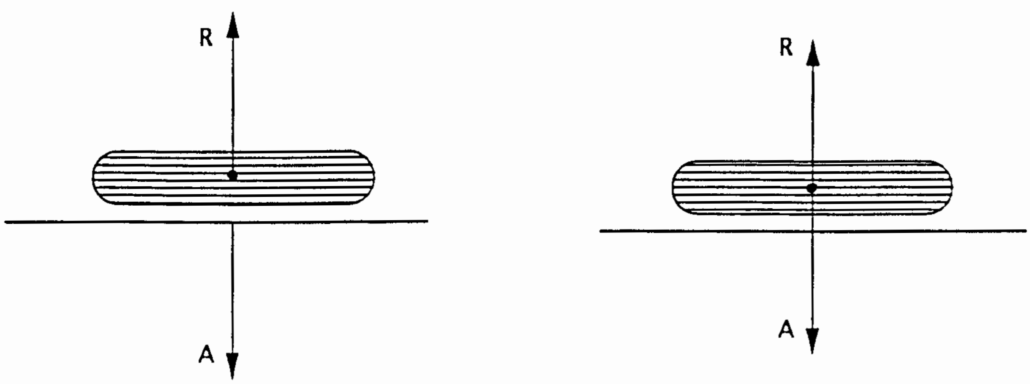
Newtonian conception Preconception

Figure 13. Path Followed by Object Whirled at the End of String at the Instant the String Breaks.



Newtonian conception Preconception

<u>Figure 14</u>. Path Followed by Object After it Leaves Curved Tube.



Newtonian conception Preconception

<u>Figure 15</u>. Action-Reaction on the Book-Table System.

the "Motion-implies-a-force" preconception, which in turn made students think that there has to be un unbalanced force in the direction of motion.

The above preconception about Action and Reaction has been also pointed out by Viennot (1979), who studied Newton's third law in problem situations involving springs. Students thought that in equilibrium positions Action and Reaction are equal, but when there is motion the Action exceeds the Reaction.

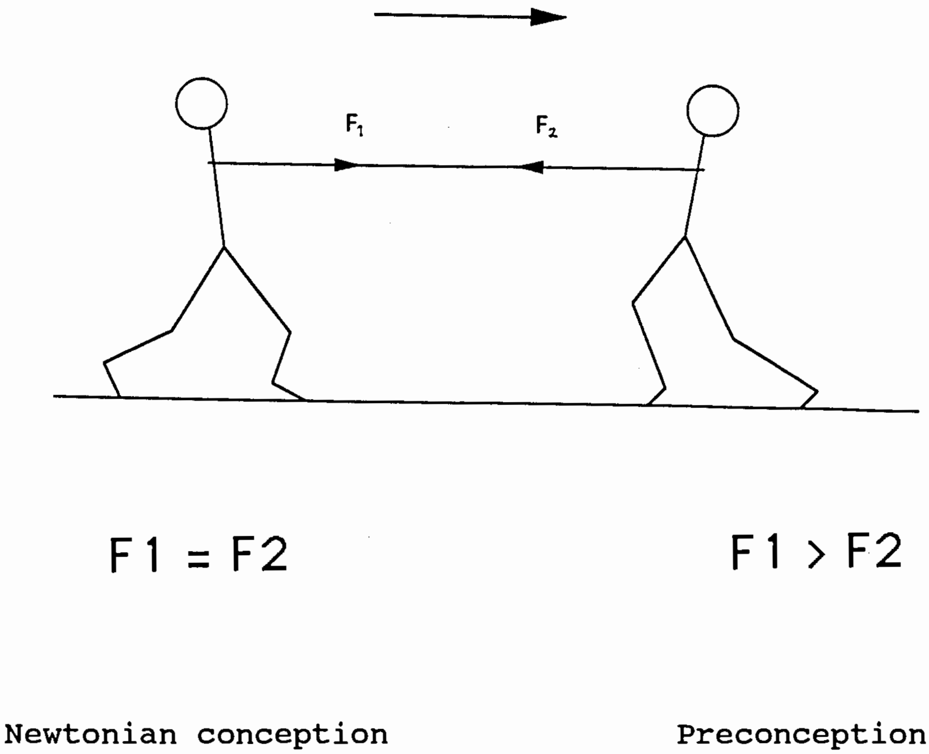
Maloney (1984) studied high school students' ideas about Action and Reaction in the context of two boxes that are in in contact (Figure 17). He identified several rules that students employ in their thinking when solving problems in this particular context. These are:

1. Mass is the only determiner for all states of motion. That is, the object with the greater mass exerts greater force.

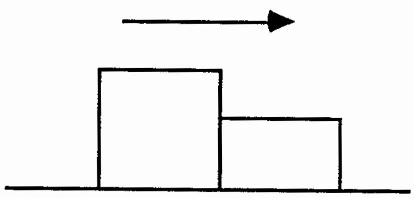
2. At rest the forces are equal, but for moving systems the object with the greater mass exerts greater force.

3. At rest the forces are equal, but for moving systems the "cause" exerts greater force.

4. For rest and constant velocity the forces are equal, but for accelerating systems the greater mass exerts greater force.



<u>Figure 16</u>. Action-Reaction in Tug-of-War Game.



<u>Figure 17</u>. Problem Situation for the Identification of Preconceptions about Action-Reaction on Two Boxes.

5. For rest and constant velocity the forces are equal, but for accelerating systems the "cause" exerts a greater force.

As it can be seen, two general rules-preconceptions that seem to be applied in situations in which there is an interaction between two bodies are the following: a) The greater mass exerts the greater force, and b) the body that causes the motion of the other exerts the greater force, because it overcomes the other's opposition.

In a more recent study with pre-physics high school students Brown (1989), found similar preconceptions about Newton's third law. He reports that 99% of the students (sample size of 78) thought that a moving ball exerts a greater force on the pin than the pin does on the ball (Figure 18). And 60% believed that in the case of two boxes which are in contact with each other, the bigger box exerts (or rather "has") a greater force.

The responses to the rest of the tasks in the questionnaire indicate that the rules identified by Maloney (1984) are applied with some consistency. In addition, Brown (1989) stressed the fact that forces are viewed as properties of single bodies rather than as relations or interactions between two bodies.

<u>Preconceptions about the path of projectiles</u>. McCloskey (1983) found that only 28% of college students predicted a parabolic path for a projectile that is launched

horizontally. The rest of the sample thought very differently, since 5% predicted that the projectile will move straight out and then straight down, and 35% believed that it first moves straight out but then curves downwards (Figure 19).

However, it is not clear from McCloskey's (1983) findings that even those students who correctly predicted a parabolic path actually understood that it involved a combination of a horizontal motion with constant velocity and an accelerating vertical motion. Halloun and Hestenes (1985b) found in their study that many students had the notion of parabolic motion, as this became evident from the responses to the multiple-choice diagnostic questionnaire. But when they conducted interviews with a small sample of 22 students to probe further the extent of students' understanding, they found that very few of them were able to recognize a parabola as a motion resulting from the composition of two different motions.

Most of the students maintained impetus ideas about projectile motion, and some of them believed that a projectile's motion is not only determined by its initial velocity, but also by how this velocity is imparted. It makes, for example, a difference whether the projectile is an object thrown by hand, or an object projected off a table, or a bomb dropped from an airplane.

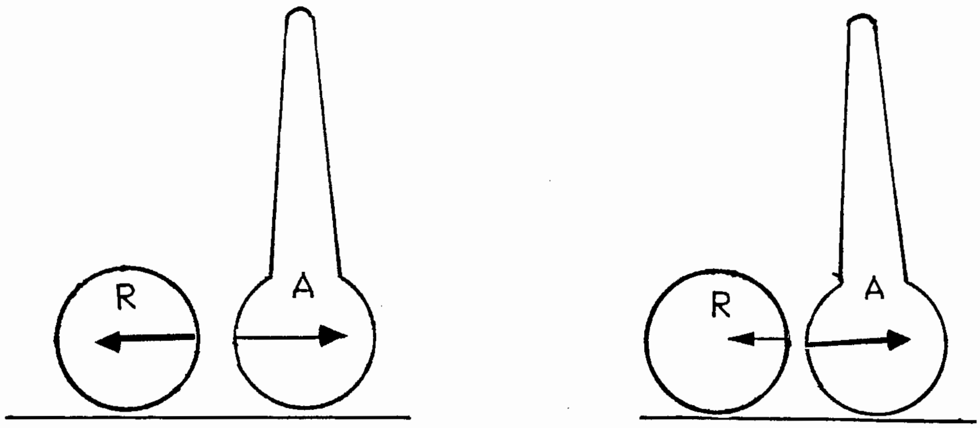


Figure 18. Action-Reaction when Ball Hits Pin.

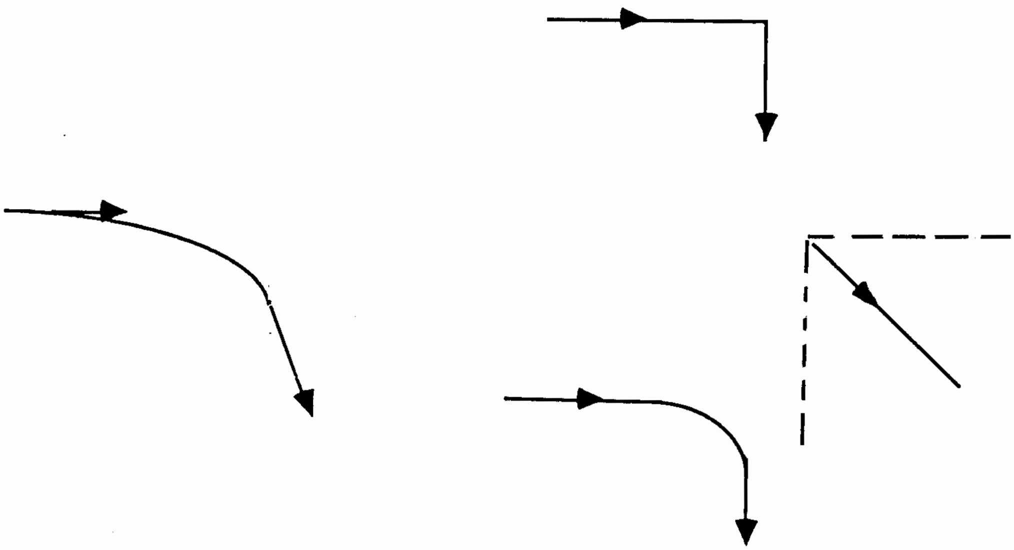


Figure 19. Path of a Horizontal Projectile.

In a more recent and more structured study, Aguirre and Rankin (1989) report on the conceptual understanding of the independence of vector components in kinematics. They presented their first-year college students who had completed a course in mechanics with an experimental situation consisting of a frictionless inclined plane (air-table). On it there was a projectile that was provided with a constant linear velocity across the incline by means of a spring-loaded plunger. This was the x-component of the velocity. The y-component was due to the the component of the force of gravity that acted because of the incline.

It was found that, only 52% (sample of 73 students) had grasped the formal vectorial treatment of composition of orthogonal component velocities. One third of the students (33%) predicted a combination of two velocities but resulting in a straight line. And 15% predicted a two-step path consisting of two straight lines, thus suggesting that the "velocity imparted to the projectile by the spring has to be dissipated before the velocity due to gravity takes over." In addition, 40% of the students entertained the preconception that the resultant motion would require more time than either of the separate orthogonal components, and 7% thought that the time for the resultant motion would be less than either of the components.

Force is the same as energy. One of the models of force identified by Viennot (1979) is what she called "supply of force." This model is used when a body is in motion, and students refer to it by saying "the force of the body." This idea is compatible with the pre-Galilean impetus theory of motion, and allows one to suggest that students might think of a force as something close to kinetic energy. However, Viennot has some reservations, for she says that it is not very clear whether students actually think of energy when they use the concept of force.

In a recent study, Boeha (1990) provides some evidence that some students do confuse force and energy, as they are employing both concepts at the same time. For example, in the context of a softball traveling in the air, some students thought that the ball has a force and this force increases as the height increases. As Boeha (1990) reports, there was a link between potential energy and force.

Osborne and Gilbert (1980) have also noted that young children hold an anthropocentric conception of force, which, in many cases is related to the concept of energy. As they noted, "the everyday use of the word force as it relates to human action tends to reinforce anthropocentric views" (p. 377), since many students could not identify a force on a bike when the biker is not pedalling.

The centripetal force is an additional force and not the resultant of all other forces. Savage and Williams (1989) studied the conceptual understanding of force in the context of circular motion. Their sample was first year science and engineering students who were to begin a course in Newtonian mechanics. They used a questionnaire in which the problem of the conical pendulum asked for the identification of all forces acting on the mass (Figure 20). The majority of students inserted a force in addition to the weight and the tension of the string.

Viennot (1979) also noticed that in the problem of a stone turning at the end of a string, students identified the tension of the string on the stone, which, however, balances the centrifugal (outward) force.

Limitations of Previous Research

Although previous research identified preconceptions about force and motion, the main focus was upon Newton's third law, as well as upon the "Motion Implies a Force" schema, as identified from the study of the trajectory of objects. No extensive study has been conducted on how students think about the motion of objects in moving frames of reference, and the factors-strategies that they consider when approaching problem tasks in this context. In addition, the conceptual link between zero resultant force and uniform motion has not been studied across a variety of contexts. These two inadequacies have not allowed researchers to assess the complete picture of physics students' Newtonian schema of motion. This study attempts, through Phenomenography and Rule Assessment Methodology, to explore the variety of concepts, relevant or irrelevant, that might exist in the students' schemata, and therefore provide a more coherent picture of how students understand.

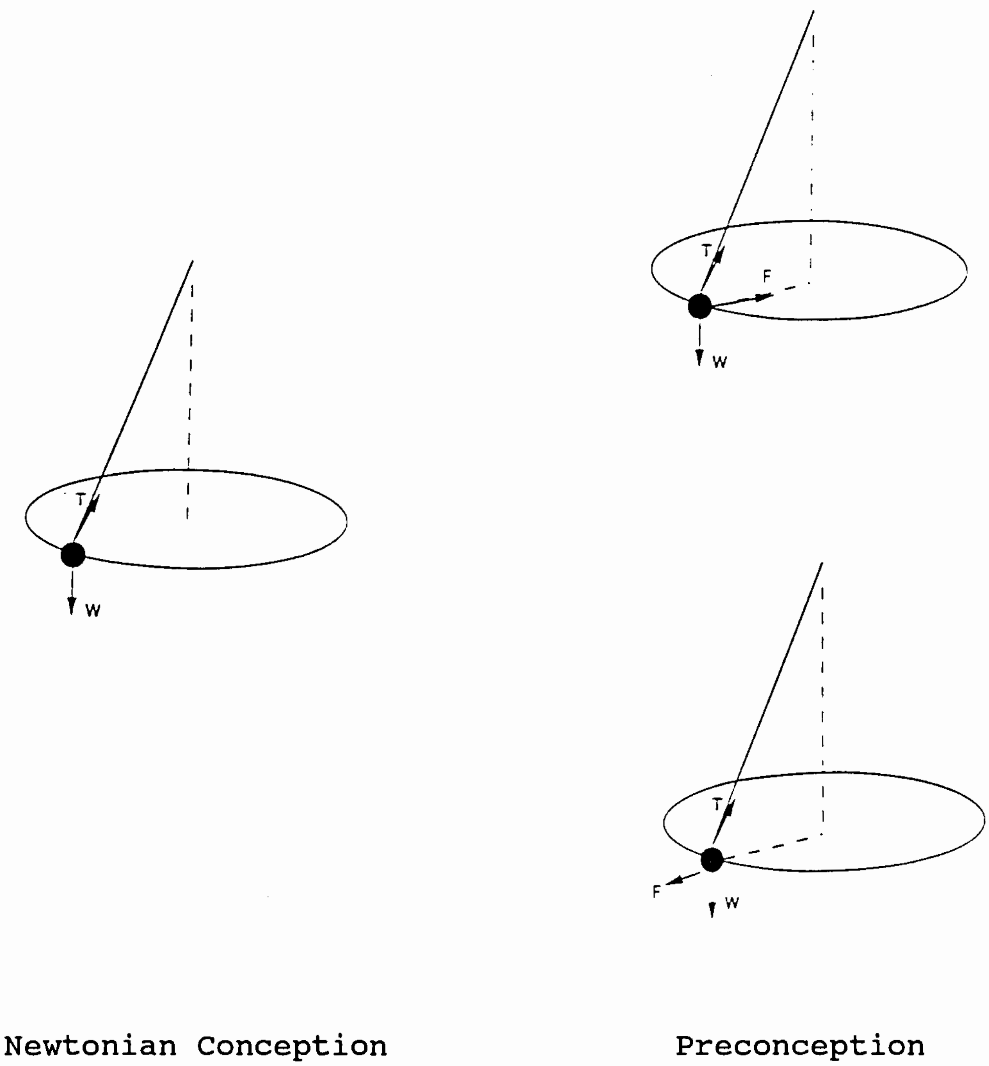


Figure 20. Forces on Conical Pendulum.

CHAPTER III

ORGANIZATION OF THE STUDY

Participants

A group of 20 students consisting of 15 males and 5 females who were enrolled in a non-calculus physics course with elements of Newtonian mechanics at the University of Northern Iowa were selected for the study. The participants were all volunteers who received 10 course grade points for their participation. Only 5 students had previously taken a physics course while in high school. For the rest of the group, the introductory physics course at the University of Northern Iowa provided the first exposure to the Newtonian concepts of force, motion, and frame of reference.

Methods and Procedures

Paper and pencil tasks in an interview mode were employed throughout the study. The advantage of using this kind of protocol instead of an unstructured clinical interview was that, while the latter has been used "to probe a student's cognitive structure in a narrowly circumscribed area of science" (Stewart, 1980), the former would be more appropriate for assessing understanding in multiple contexts which had to be designed in advance and checked for content validity.

Each student was interviewed for approximately one hour. All 20 interviews were audio-tape recorded so that validity checks could be made on certain responses after transcription. The place as well as the days on which the interviews took place, were selected by the students themselves. This approach to scheduling was employed to help them feel more comfortable without undue constraints of time.

Before each interview started I explained that the purpose of the study was to identify whatever ideas and beliefs the students employ in their understanding, and not right or wrong answers to the various problem tasks. I thought that this would encourage students to give whatever ideas they might have had without the fear of being wrong, something that could bias, and at the same time limit, the reliability of the instrument.

During the interview I also tried to be as unobtrusive as possible by asking questions such as "how do you think about that?" why is this so?" "can you explain this further?" and so forth without showing any signs that the response to a given problem task might have been non-acceptable. Even the "why" type of questions were avoided in order for students not to feel that they were being questioned about a wrong response. Only when it was thought necessary a "why" type of question was asked. However, that question was not a mere inquiring "why," but rather in the form "why is this so?" and in a tone of voice that suggested encouragement and reassurance. Before the presentation of the problem tasks, however, a short clinical interview helped me with assessing whether students had any prior knowledge, both declarative and procedural, related to the concept of motion, as well as specific contexts in which that knowledge is used (Appendix C). During the clinical interview, the students were asked to support their knowledge with as many examples as they could give. This gave me the opportunity to speculate, and probably make inferences, about why students had conceptual problems in the problem tasks that were used during the course of the interview.

Although concept mapping is a way to probe a student's cognitive structure, and specifically its organization (Heinze-Fry & Novak, 1990; Novak & Gowin, 1984; Stewart, 1980), concept mapping was not considered as an assessment instrument due to the fact that students would need time to become familiar with it and practice. In addition, concept mapping could only assess declarative knowledge through the identification of links among the various concepts, without any reference to procedural knowledge.

After the identification of prior knowledge, the students were presented with several tasks out of a wide variety of contexts. The sequence of the presentation of the problem tasks during the interview was entirely fixed but the follow-up questions varied according to each interviewee's mode of reasoning. In order to facilitate students' demonstration of the extent of the coherence of their conceptual framework, the tasks were grouped into three major categories. These categories are discussed in detail in the section on instrumentation.

Before the presentation of the problem tasks of each category, I explained the general problem situation. I assumed that this explanation would provide a framework, or organizer, which could help subsume the specific problem tasks, and also help students relate whatever factors they might have had in their schema to the general problem situation. In addition, this technique would also minimize the effect of random responses, probably influenced by an isolated problem situation, a certain linguistic, or a visual representation. The problem tasks were presented orally, while simultaneously the students were shown drawings representing the tasks in question.

During the interviews and while solving problem tasks, the students were requested to think aloud and explain their predictions. Special attention was given to the students' explanations and general reasoning process, so that possible ambiguities were eliminated. For this reason, the students were requested to compare and contrast specific problem tasks, in order to identify similarities and differences, if any, that might have led them (students) to respond the way they had. This, of course, might also have resulted in conceptual change, since the disequilibration that accompanied apparent contradictions might have very well led students to reconsider previous ideas, and influence their responses to the rest of the tasks as well. This, however, is a limitation of any study involving an interaction between a student and a researcher. But since the purpose of the study was to identify the preconceptions that the students had, only the initial conception, after it was clarified, was used for the analysis.

Special attention was also given to the identification of the frame of reference relative to which the motion of the body in question takes place, as well as to the identification of the forces acting on that body. The above clarifications helped me with providing a more valid interpretation of preconceptions, and hence, a more valid inference about the students' schematic structure.

The model shown in Figure 21 was used to guide the analysis and interpretation of the data. Similar responses to a particular problem task were grouped in different categories, and then for each category patterns of reasoning strategies were identified. For the same response was arrived at through a different strategy (see section on strategies in Chapter V). These strategies were then compared with the accepted Newtonian conception in order for the preconception(s) to be identified. After the identification of both strategies and preconceptions, an attempt to give an interpretation of the representation of the students' schema was made.

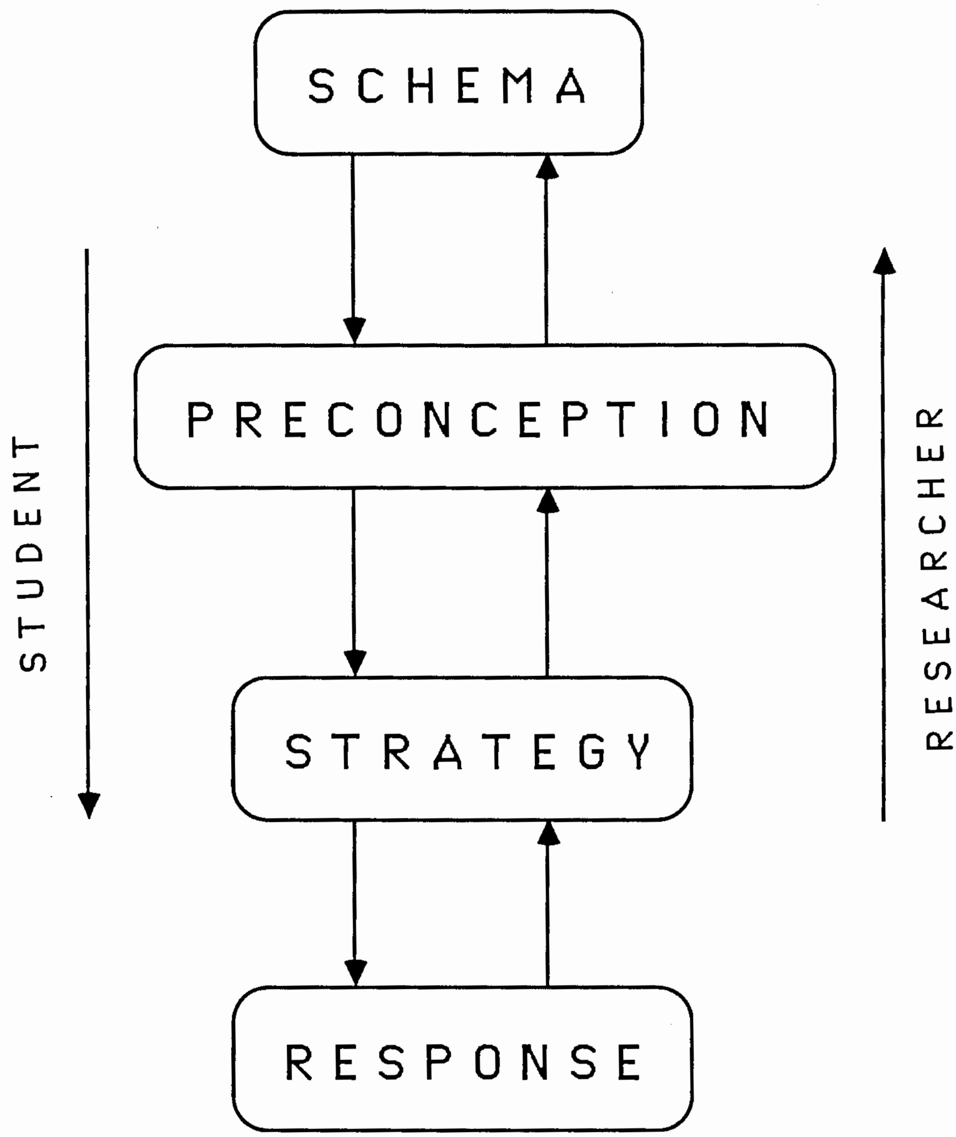


Figure 21. A Research Model for the Assessment of the Schematic Structure.

As can be seen in Figure 21 the student's schema leads to a certain response through a preconception and reasoning strategy. For the interpretation of the responses the researcher moves in the opposite direction. Although it appears that the relationship between preconceptions and schematic structure is a dialectical one, in the sense that they both evolve and develop through a two-way interaction--a preconception contributes to the development of the schema, while the latter reinforces, or modifies that preconception, or helps develop a new one--the linear model that was proposed facilitated the analysis and interpretation of the data.

Instrumentation

Starting from the premises that human cognition proceeds from the general to the more specific, rather than in the reverse direction (Ausubel et al., 1978; Gardner, 1987), and that understanding involves the restructuring of ideas and experiences one already has rather than the taking in of new ideas and experiences (Driver & Bell, 1986), it is imperative that an assessment of understanding start from a familiar problem situation in which students are asked to identify the concept or principle involved. For this reason the tasks of the interview did not address specific laws, for example, "what would happen, or how would you explain or predict this according to the First Law of Motion?" Instead, the tasks were designed in such a way as to identify reasoning patterns out of a wide variety of everyday contexts. All contexts were carefully designed so that they could facilitate access to students' relevant schemata, and at the same time help me with identifying the strategies and preconceptions derived from those conceptual schemata.

In designing problem tasks I took into account the Phenomenographic Approach to investigating different understandings of reality (Bowden et al., 1992; Marton, 1986), and the Rule Assessment Methodology (Siegler, 1978), as has been used by Maloney (1984, 1985). The Phenomenographic Approach is based on the notion that people perceive, conceptualize, and understand each phenomenon in the world in a limited number of qualitatively different ways. Therefore, understanding is contextual, and a given concept could be understood differently by different students. The different types of understandings are categorized without reference to the scientific conception. However, unlike Phenomenography, I further attempted, as has already been pointed out in the Methods section, to identify preconceptions for those categories--which I call reasoning strategies.

The Rule Assessment Methodology is based on empirical research conducted by Siegler (1978), who, in replicating Piaget's balance beam problem, found that children employ with consistency a number of rules or strategies. Maloney

(1984, 1985) in two follow up studies applied Siegler's findings in order to identify the strategies, or rules, students use in solving problem tasks involving Newton's third law and conservation of mechanical energy. Maloney, in order to identify those strategies, generated a complete list of possible factors that a student might think of while approaching a particular problem task. The problem task used by Maloney (1984) for the identification of strategies in regard to Newton's third law can be seen in the section of the literature review in the fourth part of preconceptions about Action and Reaction.

Although it appears that Phenomenography and Rule Assessment Methodology share such notions as "categories of understanding," "rules," or "strategies," the latter could be seen as an extension of the former. The reason for this is that Rule Assessment Methodology enables the researcher to identify in advance the categories that might exist in a student's schema. These categories could be seen as the research hypothesis, which will be either confirmed or rejected.

For the present study, I grouped the tasks into three categories. The first category assessed the understanding of the notion that uniform straight line motion is relative, as well as the idea that uniform straight line motion and rest are fundamentally equivalent. It also assessed the notion that motion in general is defined relative to an inertial frame of reference. The second category assessed whether students view the earth as a frame of reference, and, therefore, whether its state motion is seen as different from its state of rest. Finally, the third category evaluated the conceptual link between zero force and uniform motion.

The content validity of the problem tasks was established in two different ways (Halloun & Hestenes, 1985a). First, the tasks were examined by a number of physics and mechanics experts, such as Dr. Mike Savage and his team from the Mechanics in Action Project, University of Leeds, England, and Dr. Roy Unruh from the University of Northern Iowa. Second, the same tasks were administered in the form of a test to ten physics graduates from the University of Leeds, and the consistency in their explanation using the accepted conceptions was noticed.

The categories, the questions and the lists of possible factors-strategies that guided the construction of tasks in each one of them were as follows:

CATEGORY 1: Motion of Bodies in Frames of Reference

General problem task questions.

1. Will two bodies that start moving with the same speed from either "end" of an inertial frame of reference in opposite directions (towards each other), and parallel to the direction of motion of the frame of reference, reach the opposite "end" simultaneously?

2. Will a body projected vertically upwards from an inertial frame of reference return to the same point?

List of factors-strategies and specific contexts.

1. The motion of a body depends upon the "openness" or the "closedness" of the frame of reference, as in the case of the motion of a ball moving on the roof of a train (Figures 22a & e), the case of the motion of a ball thrown straight up by a running person (Fig. 22f), and the case of the motion of a ball inside the car compartment of a train (Figures 22b & d). Probable strategy: Motion relative to the train when motion takes place inside the train, and relative to the ground when motion takes place outside the compartment of the train, or the human body.

2. The motion of a body depends upon the direction of its motion, that is, parallel or perpendicular to the direction of the motion of the frame of reference as in the case of the motion of a ball in the direction of the train's motion (Figures 22a & b), and in the vertical direction (Figures 22d & e). Probable strategies: Motion relative to the ground for motion parallel to the direction of motion of the frame of reference, and motion relative to the frame of reference for motion perpendicular to its (frame of reference) direction of motion.

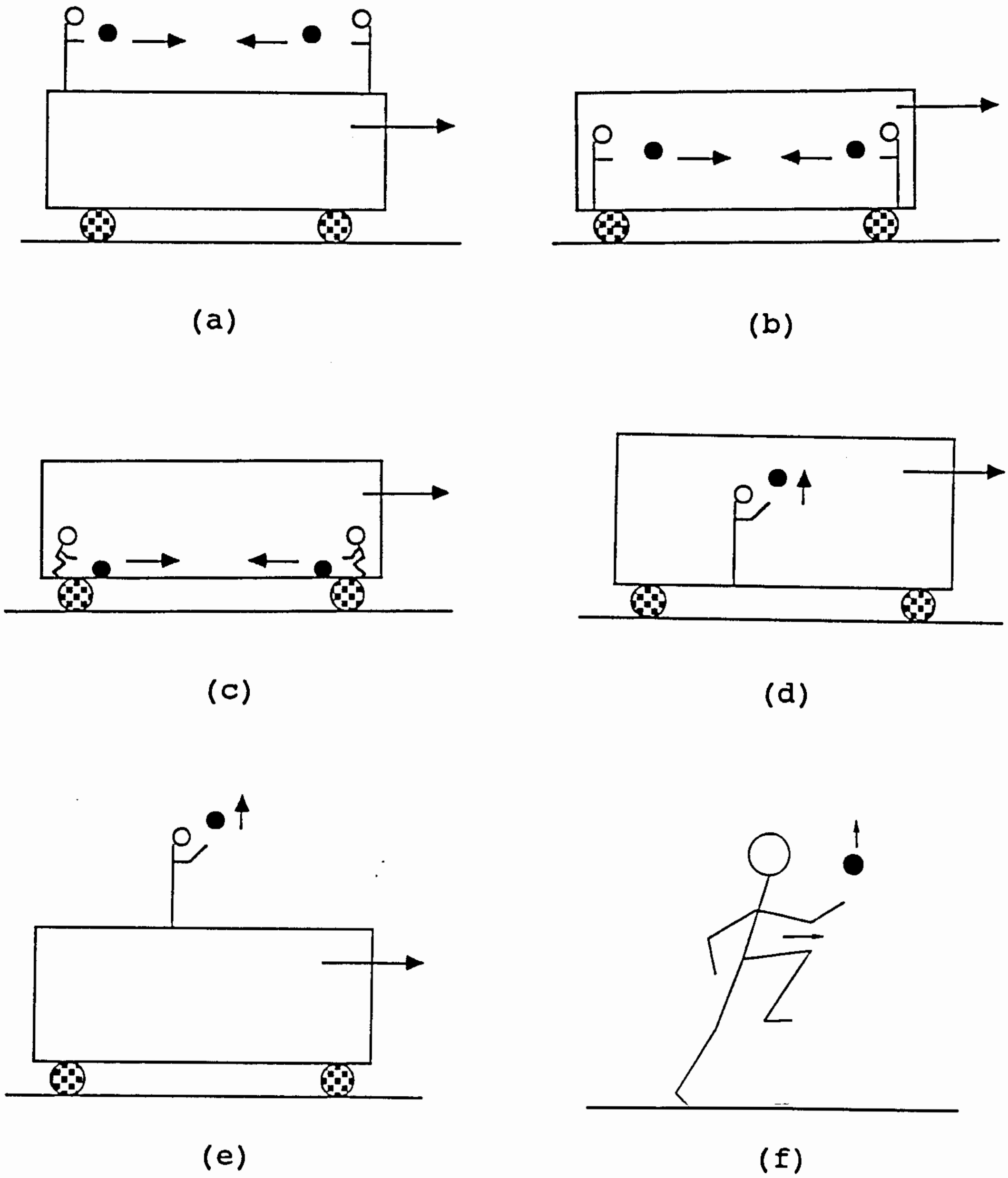


Figure 22. Problem Tasks for Assessing Understanding of Motion of Object in Frame of Reference. (Explained in Text)

3. The motion of a body depends upon whether it is in contact with the frame of reference, as in the case of a ball rolling on the floor of a train (Figure 22c). Probable strategies: Motion either relative to the ground or relative to the frame of reference.

CATEGORY 2: Motion of Bodies on the Inertial Frame of Reference of the Earth

General problem task questions.

1. Will a body projected vertically upwards from the earth, modeled both as "flat motionless surface" and as "flat surface moving with constant velocity," return to the same point?

2. Where will a body dropped from a point high above the ground, modeled as "flat surface moving with constant velocity," land?

3. Will two bodies moving with equal speeds around the earth along the equator, but in opposite directions, arrive at the starting place simultaneously?

List of factors-strategies and specific contexts.

1. The motion of a body projected straight up in the air is viewed as motion from "flat motionless ground" as in the case of the motion of a stone (Figure 23a), the motion of a cannon ball (Figure 23b). Probable strategy: Motion relative to the ground.

2. The motion of a body projected straight up in the air from the ground, modeled as "a flat surface moving with constant velocity," is viewed from space as in the case of

the motion of a rocket (Figure 23c). Probable strategy: Motion relative to the space (fixed stars).

3. The motion of a body moving vertically from the earth, modeled as "a flat surface moving with constant velocity" depends upon the earth's atmosphere, as in the case of a hot-air balloon (Figure 23d). Probable strategy: Motion relative to the earth.

4. The motion of a body dropped from a large height to the ground, modeled as "a flat surface moving with constant velocity," is dependent upon the existence of a reference point on the surface, as in the case of an iron ball dropped from an imaginary hand that remains fixed in space (relative to the stars) (Figure 23e), from an imaginary hand remaining fixed in space near the top of the building (Figure 23f), and from the top of a building (Figure 23g). Probable strategies: Motion relative to space when no building is present, relative to the ground when a building is present.

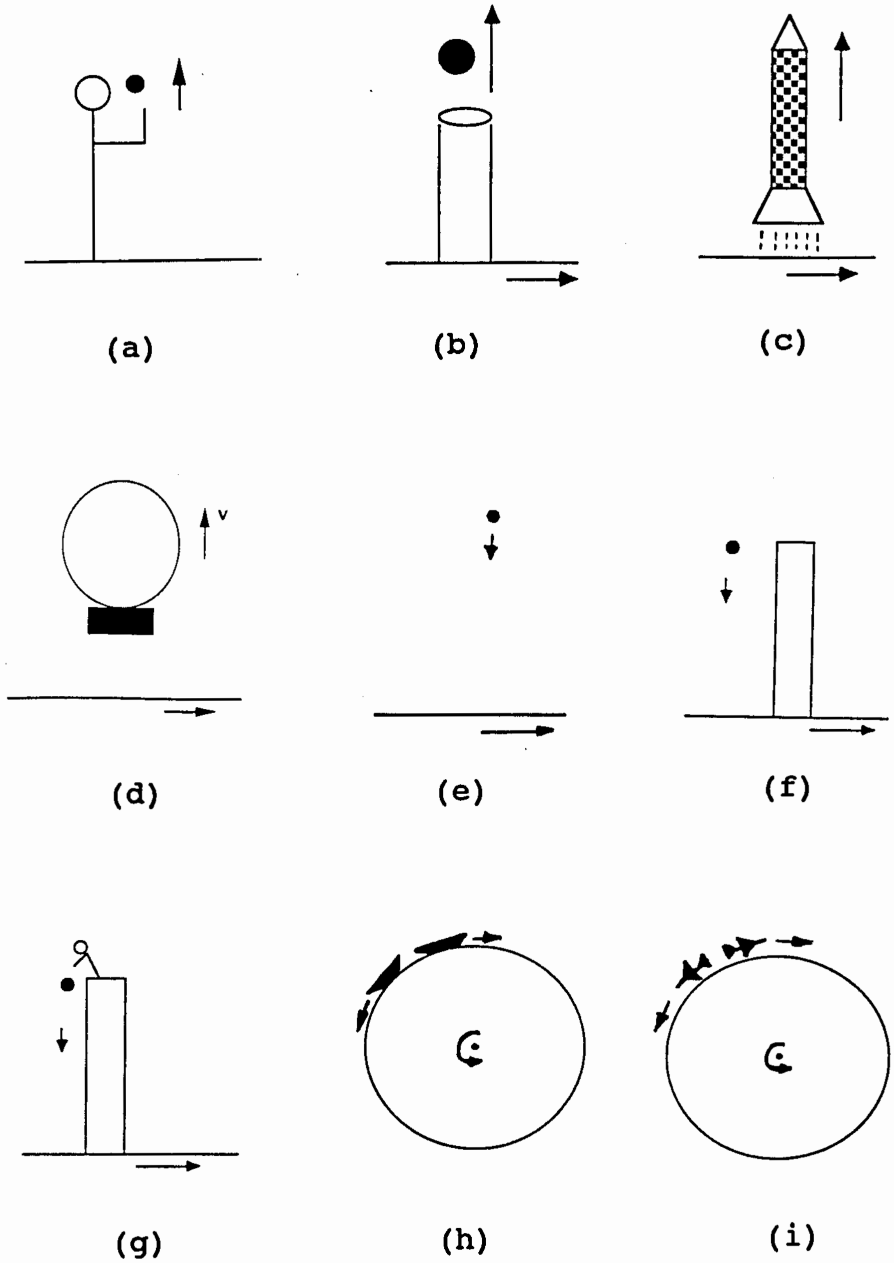


Figure 23. Problem Tasks for Assessing Understanding of Motion of Object in Frame of Reference of Earth. (Explained in text)

5. The motion of a body on the frame of reference of the earth depends upon whether the body is in contact with the earth's surface, as in the case of two boats (Figure 23h), and two airplanes (Figure 23i) sailing and flying respectively around the earth. Probable strategies: Motion relative to the space for case of the airplanes, and motion relative to the space or earth for the motion of the boats.

<u>CATEGORY 3: Motion of Bodies with Constant Velocity</u>

<u>General problem task questions</u>.

1. Is a net force acting on a body moving with constant speed in straight line?

<u>List of factors and specific contexts</u>.

1. The conceptual link between zero net force and uniform straight line motion depends upon the kind of the moving object (e.g., a spaceship, car, box).

2. The conceptual link between zero net force and uniform straight line motion depends upon episodic knowledge (e.g., a car on a "windy" day, a box being pushed along the floor by a person, objects hanging from strings inside cars, boxes being lifted from the floor).

3. The conceptual link between zero net force and uniform straight line motion depends upon the mass of the moving body (e.g., a bicycle, car, truck).

CHAPTER IV

ANALYSIS OF RESPONSES

This chapter groups the responses, as given by the 20 students to each task of all three categories, without any attempt to interpret them. (The responses to the clinical interview appear in quotations in the chapter of Interpetation and Discussion.) For each task there is the accepted response (in accordance with the Newtonian conception) and the alternative response(s). The number of students for each response is also given.

Category 1: Motion of Bodies in Frames of Reference

This category deals with two general problem situations addressed through different contexts. The first situation and the responses (collectively and individually) can be seen in Tables 1 and 2, while the second situation is presented in Tables 3, 4 and 5. Below are the specific tasks and the respective responses to those two problem situations.

Task 1: Two friends are standing on either end of the roof (outside) of a train moving with constant speed in straight line. Suddenly they each throw the balls they are holding to each other. What can you say about the time the balls take to reach the other person? The velocities and the masses of the balls are the same, and the effect of air resistance is negligible.

Accepted responses: Neglecting air resistance, both friends will catch the balls simultaneously as if the train were at rest because it does not make a difference whether the train is at rest or in motion (n = 0).

Or, the motion of the balls is considered relative to the frame of reference of the train, which is an inertial frame of reference and therefore both friends will catch the balls simultaneously (n = 0).

Alternative response 1: The person in the rear will catch the ball first because he is moving towards the ball (n = 17).

Alternative response 2: The person in the front will catch the ball first because the ball is approaching him with higher velocity . The ball has, in addition to its own velocity, the velocity of the moving train (n = 2).

Task 2: Two friends are standing on either end (inside) the car compartment of a train moving with constant speed in straight line. Each is holding a ball in his hands. Suddenly they both throw their balls simultaneously to each other. What can you say about the time the balls will take to reach the person on the opposite end? The velocities and the masses of the balls are the same.

Accepted responses: Taking into account the conception that uniform straight line motion and rest are equivalent, both friends will catch the ball simultaneously (n = 0).

Or, the motion of the balls is considered relative to the frame of reference of the train, and therefore both friends will catch the balls simultaneously ($\underline{n}$ = 3).

Alternative response 1: Both friends will catch the ball simultaneously because the balls are moving along with the train because the train is a closed system ($\underline{n}$ = 4), but if the air were pumped out of the train the friend in the rear would catch the ball first because this situation would be the same as being outside on the roof of the train ($\underline{n}$ = 2).

Alternative response 2: The friend in the rear will catch the ball first because he is moving towards the ball ($\underline{n}$ = 11).

Alternative response 3: The friend in the front will catch the ball first because the ball is approaching him with greater velocity. The ball has, in addition to its own velocity, the velocity of the train ($\underline{n}$ = 2).

Task 3: Two friends are standing on either end (inside) of the car compartment of a train moving with constant speed in straight line. Suddenly they both roll a ball to each other. What can you say about the time it will take the balls to roll to the other person?

Accepted responses: Taking into account the conception that uniform straight line motion and rest are equivalent, both friends will catch the ball simultaneously ($\underline{n}$ = 0).

Or, the motion of the balls is considered relative to the frame of reference of the train, which is an inertial frame of reference, and therefore both friends will catch the balls simultaneously (n = 3).

Or, both friends will catch the balls at the same time because the balls are in contact with the train and they therefore participate, in the motion of the train (n = 5).

Alternative response: The friend in the rear will catch the ball first because he is moving towards the ball (n = 12).

Task 4: A person is sitting in the car compartment of a train traveling with constant speed in straight line. Suddenly he throws a softball a small way straight up in the air. Where will the softball land? The force the person is applying is in the vertical direction.

Accepted responses: The softball will fall straight back down into the person's hands because its motion is not affected by the uniform motion of the train (n = 0).

Or, the motion of the softball is relative to the frame of reference of the train and therefore it will fall straight back down (n = 3).

Or, the softball will fall straight back down because it will continue to move in the direction of the train's motion (n = 5).

Alternative response 1: The softball will land behind the person because he is moving forward along with the train while the ball is moving upwards (n = 5). (Three of those five students believed that a person on the train sees a straight line path of the softball, and a person on the ground sees a curved path, while two students believed the opposite.)

Alternative response 2: The softball will fall straight back down because it will continue to move in the direction of the train's motion due to a force that carries the softball forward (n = 7).

Task 5: A person is standing on the roof of a train moving with constant speed in straight line. Suddenly he throws a softball straight up in the air. Where will the softball land if the effect of wind and air resistance are negligible?

Accepted responses: Neglecting the effect of wind and air resistance, the softball will fall straight back in the person's hands because the motion of the softball is not affected by the uniform motion of the train (n = 0).

Or, the motion of the softball is considered relative to the frame of reference of the train, and therefore it will move straight up and then fall straight down and will land in the person's hand (n = 0).

Table 1

<u>Number of Responses to Problem Situation of Two Persons Standing On Either End of Car Compartment of Train and Throwing or Rolling to Each Other the Ball They are Each Holding</u>

TASK	RESPONSE A: Accepted Both persons catch the balls at the same time	 B: Alternative Either person catches the ball first	FRAME OF REFERENCE FOR RESPONSE A Train	 Ground	FRAME OF REFERENCE FOR RESPONSE B Train	 Ground
1	1	19	1		3	16
2	5	15	4	1	3	12
3	8	12	7	1	2	10

Table 2

Responses of Individual Students to Problem Situation of Two Persons Standing on Either End of Car Compartment of Train and Throwing or Rolling to Each Other a Ball They are Each Holding

TASK	RESPONSES: Both persons catch the balls at the same time	RESPONSES: Either person catches the ball first
1	I	A, B, C, D, E, F, G, H, J, K, L, M, N, O, P, Q, R, S, T
2	I, J, K L, M, Q, R	A, B, C, D, E, F, G, H, N, O, P, S T
3	I, J, K L, M, N, O, P	A, B, C, D, E, F, G, H, Q, R, S, T

Or, the softball will land in the person's hand because the softball continues to move in the forward (horizontal) direction while it is going up and down in the air (n = 5). (Three of these five students believed that there is a force that carries the softball forward.)

Alternative response 1: The softball will land behind the person because he is moving forward, while the softball is moving up and down in the air (n = 10).

Alternative response 2: The softball will land behind the person because the softball is moving outside the frame of reference (n = 5).

Task 6: A person is holding a baseball in his hand while running with constant speed in a straight line. Suddenly (and while he is in uniform straight line motion) he applies a vertical force to the baseball and the ball starts moving vertically upwards in relation to the person's body. Where will the baseball land?

Accepted responses: The baseball will fall straight back in the person's hands because the motion of the ball is not affected by the uniform motion of the person's body (n = 0).

Or, the baseball will fall straight back in the person's hand the because the ball continues to move in the forward direction while it is going up and down in the air. This situation is similar to that of the train (n = 1).

Alternative response 1: The baseball will land behind the person because he is moving forward, while the baseball is moving up and down in the air (n = 14).

Alternative response 2: The baseball will land behind the person because the earth is the frame of reference (n = 5). (All five students believed that the human body is not a frame of reference.)

Table 3

Number of Responses to Problem Situation of Person Throwing Softball Straight Up in Air from Frame of Reference

TASK	RESPONSE A: Accepted The ball falls straight back to the person's hand	 B: Alternative The ball lands behind the person	FRAME OF REFERENCE FOR RESPONSE A Train	 Ground	FRAME OF REFERENCE FOR RESPONSE B Train	 Ground
4	15	5	7	8	2	3
5	5	15	1	4	4	11
6	1	19		1		19

Table 4

Responses of Individual Students to Problem Situation of Person Throwing Softball Straight Up in Air from Frame of Reference

TASK	RESPONSE: The ball falls straight back to the person's hand	RESPONSE: The ball lands behind the person
4	I, J, K, L, M, N, O, P, Q A, B, C, D, E, F	G, H, R, S, T
5	I, J, A, B, N	C, D, E, F, G, H, K, L, M, O, P, Q, R, S, T
6	J	A, B, C, D, E, F, G, H, I, K, L, M, N, O, P, Q, R, S, T

Table 5

Responses to Same Problem Situation of Person Throwing Ball Straight Up From Inertial Frame of Reference in Different Contexts Show Pattern of Consistency in Thinking of Students

CONTEXT: ball thrown inside the compartment of a train	ball thrown from the roof of the train	ball thrown from a person running on the ground	*n*
Response: The ball always lands behind the person			5
Response: The ball lands in the person's hand when the person is inside the train, but behind the person if he/she is on the roof (outside) of the train or running			10
Response: The ball lands in the person's hands if he/she is on the train (inside or outside), but behind the person if he/she running on the ground			4
Response: The ball always lands in the person's hands			1
Total Number of Students			20

Category 2: Motion of Bodies on the Frame of Reference of the Earth

This category deals with three general problem situations. The first problem situation and the responses (collectivelly and individually) in different contexts are presented in Tables 6 and 7. The second problem situation and the responses to this situation can be seen in Table 8, while the responses to the third problem situation are shown in Tables 9 and 10. Below are the specific problem tasks responses to these tasks.

Task 7: A person is standing in his backyard holding a rock. He suddenly throws it straight up in the air. Where will the rock land?

Accepted response: The rock will land in the person's hands because the rock has only a vertical (component of) velocity (n = 20).

Task 8: A cannon is firing a cannon ball straight up in the air. Will the cannon ball return to the same point on the ground? The earth is considered a non-rotating frame of reference moving with constant speed in straight line.

Accepted responses: Assuming that there are no external forces except for the weight acting on the cannon ball as it is traveling through the air, the cannon ball will return to the same point on the ground because its motion is considered relative to the frame of reference of the earth (n = 0).

Or, the cannon ball returns to the same point because, the cannon ball has, apart from a vertical velocity, a horizontal component equal to the velocity of the earth's surface that remains constant during its flight (n = 0).

Or, the cannon ball will return to the same point because this situation is similar to that of the softball thrown straight up in the air from the roof of the train. The cannon ball is moving up and down in the air but it also has the horizontal velocity of the earth. Its path is parabolic (n = 2).

Alternative response 1: The cannon ball will not return to the same point because as it is going up and down in the air, the earth has moved considerably (n = 17).

Alternative response 2: The cannon ball will land at a point on the ground that is far ahead of the point of projection because the cannon ball has also the velocity of the moving earth (n = 1).

Task 9: A rocket is fired vertically from the ground. The rocket travels straight up until all its fuel is used up and then starts falling straight down. Will the rocket return to the same point on the ground, that is, to the point from which it originally took off? The effect of wind and air resistance are considered negligible. The only force acting on the rocket on its way back to the ground is its weight.

Accepted responses: Assuming that there are no external forces except for the weight acting on the rocket as it is traveling in the air, it will return to the same point on the ground because its motion is considered relative to the frame of reference of the earth. The path of the rocket is a straight line ($\underline{n}$ = 0).

Or, the rocket will return to the same point because, at the moment it leaves the ground, the rocket has, apart from a vertical velocity, a horizontal component equal to the velocity of the earth's surface which remains constant throughout its flight. The path of the rocket is a parabola ($\underline{n}$ = 0).

Or, the rocket will return to the same point because this situation is similar to that of the softball thrown straight up in the air from the roof of the train. The rocket is moving up and down but it also has the velocity of the earth. The path of the rocket is a parabola due to the composition of two components of velocity, the vertical component and the horizontal one ($\underline{n}$ = 2).

Alternative response: The rocket will not return to the same point because as it is going up and down in the air, the earth has moved considerably ($\underline{n}$ = 18). (Three students believed that the rocket is not in the frame of reference of the earth because the rocket is moving away from the surface of the earth.)

Task 10: An air-balloon is rising vertically above the ground. After it goes up high, it stays there for some time, and then comes back down again. Will it land on the point from which it took off?

Accepted responses: Assuming that the only forces acting on the balloon are its weight and the force of buoyancy, both acting in the vertical direction (the weight in the downward direction and the buoyancy in the upward direction), the balloon will land to the same place. Its motion--straight up and down--is relative to the frame of reference of the earth ($\underline{n}$ = 0).

Or, the balloon returns to the point from which it took off because it is moving along with the earth's atmosphere ($\underline{n}$ = 3).

Alternative response 1: The balloon will never land at the same point because the earth has moved while the balloon was going up and down. The path of the balloon is a straight line ($\underline{n}$ = 16).

Alternative response 2: The balloon will not land at the same point because it stays motionless for some time ($\underline{n}$ = 1).

Table 6

Number of Responses to Problem Situation of Vertical Projection of Object from Ground

TASK	RESPONSE A: Accepted The object returns to same point on the ground	RESPONSE B: Alternative The object cannot return to the same point on the ground	FRAME OF REFERENCE FOR RESPONSE A Earth	FRAME OF REFERENCE FOR RESPONSE A Space	FRAME OF REFERENCE FOR RESPONSE B Earth	FRAME OF REFERENCE FOR RESPONSE B Space
7	20		20			
8	2	18	1	1	2	16
9	2	18		2	2	16
10	3	17	3		2	15

Table 7

Responses of Individual Students to Problem Situation of Vertical Projection of Object From Ground

TASK	RESPONSE: The object returns to the same point on the ground	RESPONSE: The object cannot return to the same point on the ground
8	I, J	A, B, C, D, E, F, G, H, K, L, M, N, O. P, Q, R, S, T
9	I, J	A, B, C, D, E, F, G, H, K, L, M, N, O, P, Q, R, S, T
10	A, B, I	C, D, E, F, G, H, H, J, K, L, M, N, O, P, Q, R, S, T

Task 11: An iron ball is dropped from a point high above the ground by an imaginary hand fixed in space. Where will it land?

Accepted responses: The motion of the iron ball can be considered relative to space (fixed stars), and therefore the iron ball will fall straight down and will land at a point that was not directly under the point of release ($\underline{n}$ = 0).

Or, the iron ball will land at a point that was not directly under the point of release because the earth has moved (n = 20).

Task 12: An iron ball is dropped by an imaginary hand that is near the top of a very high building. Where will it land?

Accepted responses: The iron ball will land at point that is far away from the foot of the building because the motion of the ball is relative to space (fixed stars) (n = 0).

Or, the iron ball will land at a point that is far away from the foot of the building because while the ball is falling the earth has moved (n = 17).

Alternative response: The iron ball will land directly under the point of release, that is, at the foot of the building because the iron ball, being near the building, is falling parallel to it (n = 3).

Task 13: An iron ball is dropped from the top of a high building. Where will it land? The only force acting on it is its weight. The effects due to the rotation of the earth is negligible.

Accepted responses: The motion of the iron ball can be considered relative to the earth (or building), and therefore it will fall straight down and will land at the foot of the building, that is, at a point directly under the point of release (n = 5).

Or, the iron ball will land at the foot of the building because the ball is also moving with the velocity of the building (n = 8).

Alternative response: The iron ball will land away from the foot of the building (to the left) because as the iron ball is falling through the air the earth has moved (to the right) (n = 7).

Task 14: Two boats set sail from the same place on the equator and they are going to sail around the earth and along the equator. The boats will sail in opposite directions with the same speeds. Will the boats arrive at the place from which they set sail simultaneously? The Coriolis effect is not taken into account.

Accepted responses: The motion of the boats is relative to the earth, and therefore they will both arrive at the place from which they set sail at the same time (n = 2).

Or, both boats will arrive at the same time because they belong in the frame of reference of the earth since they are in contact with the earth (n = 2).

Alternative response: The boat sailing west will arrive first because the earth is moving towards it (n = 16).

Table 8

Number of Responses to Problem Situation of Dropping of Iron Ball from Height Above Ground by Considering Only Weight of Iron Ball

	RESPONSE		FRAME OF REFERENCE FOR RESPONSE A		FRAME OF REFERENCE FOR RESPONSE B	
	A: Accepted	B: Alternative				
TASK	The iron ball hits the ground at a point that is under the point of release	The iron ball will hit the ground at a different point	Earth	Space	Earth	Space
12	3	17	3		4	13
13	13	7	5	8	2	5

Task 15: Two airplanes are taking off from the same place on the equator, and are flying around the earth parallel to the equator but in opposite directions and with equal speeds. Will the planes arrive at the take-off place simultaneously? The Coriolis effect and forces due to wind are not taken into account.

Accepted response: Neglecting air resistance and the effect of wind, both planes will arrive simultaneously because their motion is relative to the frame of reference of the earth ($\underline{n}$ = 0).

Alternative response: The plane flying due west will arrive first because it is flying towards the place from which it took off ($\underline{n}$ = 20).

Category 3: Motion of Bodies with Constant Velocity

This category deals with the motion of an object with constant speed in straight line. The responses and the different contexts in which students were requested to assess whether there is a net force acting on the object in question are summarized in Table 11. Following are the responses to the specific tasks.

Task 16: A spaceship is traveling in outer space with constant velocity. The spaceship is not acted upon by any planetary forces. The force exerted by interplanetary dust is also negligible. Do you think there is a net force acting on the spaceship as it is moving in outer space with constant velocity?

Table 9

Number of Responses to Problem Situation of Motion of Two Objects Traveling Around Earth

	RESPONSE		FRAME OF REFERENCE FOR RESPONSE A		FRAME OF REFERENCE FOR RESPONSE B	
	A: Accepted	B: Alternative				
TASK	The objects will arrive at the point from which set off at the same time	The object that is moving due west will arrive first	Earth	Space	Earth	Space
14	4	16	4		1	15
15	0	20			1	19

Table 10

Responses of Individual Students to Problem Situation of Motion of Two Objects Traveling Around Earth

TASK	RESPONSE: The objects will arrive at the point from which the set off at the same time	RESPONSE: The object moving due west will arrive first
14	I, J M, N	A, B, C, D, E, F, G, H, K, L, O, P, Q, R, S, T
15		ALL

Task 16: A spaceship is traveling in outer space with constant velocity. The spaceship is not acted upon by any planetary forces. The force exerted by interplanetary dust is also negligible. Do you think there is a net force acting on the spaceship as it is moving in outer space with constant velocity?

Accepted response: There is no net force acting on the spaceship because it is moving with constant velocity (n = 12). (Six of those 12 students believed that the spaceship is not acted upon by a net force because, once set in motion, there are no forces to slow it down.)

Alternative response 1: There is a net force in the direction of motion. It is the reaction to the action of the engine which is exerted on the ejected fuel ($\underline{n}$ = 4). (All four students believed that the force acting on the spaceship is constant, otherwise the spaceship would accelerate, and also that the constant velocity of the spaceship is due to the fact that the force on it is applied discontinually, since action and reaction are not continuous forces.)

Alternative response 2: There is a net force acting on the spaceship because it is moving ($\underline{n}$ = 4). (Three students believed that the force that set the spaceship in motion must be applied continuously otherwise the spaceship would travel a certain distance and stop, and two of them also believed that the force acting on the spaceship has a constant magnitude, because constant magnitude forces produce and maintain constant velocity and forces of increasing magnitude produce acceleration.)

Task 17: A car is traveling against a strong wind but the driver manages to keep the car in a straight line with constant speed. Do you think there is a net force acting on the car?

Accepted response: There are two forces in the horizontal direction, one exerted by the ground and the other by the air, but the net force is zero because the car is moving with constant velocity ($\underline{n}$ = 4).

Alternative response: There are two forces but the force exerted by the engine of the car is greater because the driver is pressing the accelerator harder in order to overcome the force exerted by the wind ($\underline{n}$ = 16).

Task 18: Three identical airplanes are traveling with constant speed in a straight line on three different occasions. The first airplane is traveling up an incline, the second is traveling along a horizontal line parallel to the ground, and the third plane is traveling down an incline. Do you think there is a net force acting on the planes? If yes, which airplane is acted upon by greater net force?

Accepted response: On all three occasions the net force is zero because the plane is always moving with constant velocity ($\underline{n}$ = 3).

Alternative response 1: The net force is zero only when the plane flies horizontally. There is force in the direction of motion when the plane flies on a slope ($\underline{n}$ = 6).

Alternative response 2: There is a net force in the direction of motion on all three occasions, but the force on the plane moving downwards is smaller because there is a component of the weight in this direction, and the force is greater when the plane is moving upwards because it has to overcome the component of the weight that is now applied in the opposite direction ($\underline{n}$ = 11).

Task 19: There are three different vehicles: A motorbike, a racing car, and a truck. They are all traveling with constant speed in straight line. Do you think there is a net force acting on these vehicles? If yes, which one is acted upon by greater net force?

Accepted response: The net force is zero on all occasions because all vehicles are moving with constant velocity (n = 1).

Alternative response: The net force on the truck is greater because it has the greatest mass (n = 19).

Task 20: A person is pushing a heavy box along the floor with constant speed in straight line. Do you think there is a net force acting on the box?

Accepted response: The net force is zero because the box is moving with constant velocity (F = T) (n = 3).

Alternative response: The force applied by the person, F, is greater than the frictional force, T, and therefore there is a net force in the direction of the motion of the box (n = 17).

Task 21: There are three identical vans. A piece of string is hanging from the roof of each van, while a bob is attached to the other end of the string. In the first van the string is tilted backward, in the second van the string is hanging straight down, and in the third van the string is tilted forward. Do you think that any of these vans is moving with constant speed in straight line?

Accepted response: The van with the string hanging straight down is moving in straight line with constant speed because there are is no force acting on the bob in the direction of motion (n = 4).

Or, since the state of rest is equivalent to the state of uniform straight line motion the van with the string hanging straight down is moving with constant speed in straight line (n = 0).

Alternative response 1: The van with the string hanging straight down is moving with constant velocity because from our experience we know that objects tied to strings hanging from rear view mirrors remain vertical (n = 13).

Alternative response 2: The van with the string tilted forward is moving with constant velocity because the string is tilted in the direction of the motion of the van (n = 1).

Alternative response 3: The van in which the string is tilted backward is moving forward with constant velocity because the string is acted upon by a force that is the reaction to the force of the car. It is about the law of Action and Reaction (n = 2).

Table 11

Responses to Problem Situation of Motion of Object with Constant Velocity (Tasks 16, 17, 18, and 20)

	RESPONSE	
	Accepted	Alternative
CONTEXT	The net force acting on the object is zero	There is a net force in the direction of the object's motion
Spaceship in outer space away from forces	12	8
Car on a windy day	4	16
Airplane flying up and down an incline	3	17
A box being pushed along the floor	3	17

CHAPTER V

INTERPRETATION OF RESPONSES

This chapter provides an interpretation of students' thinking during the clinical interview and their responses to the 21 problem tasks that followed. The chapter is divided into six major sections according to the original research questions:

1. On the understanding of the qualitative definition of uniform straight line motion: Is uniform straight line motion understood as being equivalent to rest?

2. On the understanding of the notions of relativity and frame of reference: Is motion defined relative to a frame of reference? What is the the preferred frame of reference across the various problem tasks? Do students use consistently the same frame of reference, or do they change the frame of reference according to the context of the task in question?

3. On the understanding of the relationship between zero net force and uniform straight line motion: Do students understand that uniform straight line motion can exist in the absence of a net force?

4. On reasoning strategies and preconceptions: What reasoning strategies do students employ in their thinking, and what preconceptions lead students to adopt these strategies?

5. On schematic representation: What schema(ta) might be inferred from the identified preconceptions?

6. On knowledge representation: What kind of knowledge representations--propositional and analogical--exist in the cognitive structure of these particular students?

The interpretation given in the first three sections is based mainly upon the students' thinking employed during the clinical interview, while the strategies and preconceptions, along with the schematic and knoweledge representation are inferred from the responses to the problem tasks of the three categories (see Chapter IV). However, the most common responses to one or two particular problem tasks, as were given by the great majority of students, are also incorporated in the discussion.

The Qualitative Definition of Uniform Straight Line Motion

The most fundamental idea of the Newtonian model of motion is the equivalence between uniform straight line motion and rest. From a Newtonian point of view no differentiation is made between an object at rest and an object moving with constant speed in straight line. The tasks of the first two categories were used to assess this equivalence. In both categories the problem tasks were about predicting the motion of an object in a frame of reference, that is, a train, the human body, and the earth, all moving with constant speed in straight line. According to the Newtonian conception, the object would move as if the train, the human body, and the earth were at rest. However, there was a difference in the thinking of students between the case of the motion of an object in the frame of reference, when the latter is at rest, and the case of the motion of the same object in the same frame of reference when the latter is in uniform straight line motion.

During the preliminary clinical interview all students were unable to find a way to determine whether they are moving with constant speed in straight line or whether they are at rest. (Students were asked to imagine themselves inside a windowless vehicle, and then find a way to tell whether they are in uniform straight line motion.) However, the difficulty that most students had in determining whether or not they are in uniform straight line motion was not related to the identification of force(s), or the performance of an experiment that could provide some evidence as to the different behaviour of an object in the vehicle, but rather to the lack of visual contact with the external world that would act as a reference point. This reference point becomes quite apparent from what three students said:

> If we cannot look outside we can't tell whether we are moving . . . we must have a reference point.

> How can we tell if we cannot look outside? If we are traveling in a car we must look outside and see other cars, and other objects like trees and houses. . . . It's always the trees and the houses going in the opposite direction that make us perceive motion.

> Without looking outside . . . I think it would be hard to tell if something is moving with constant speed.

It should be mentioned, though, that six other students did make a reference to "feeling," that is, whether or not they would feel anything inside the vehicle, but they nevertheless reasoned that, since there is no acceleration, they would not feel anything. The following are the actual words of four students who made explicit reference to "feeling:"

> I don't know . . . I suppose it's very difficult to tell if we are moving with constant speed . . . we don't feel anything.

> If the vehicle does not accelerate . . . I don't think we can say whether we are moving with constant velocity.

> If I don't feel any forces when I'm inside the vehicle . . . I cannot tell whether I am at rest or in motion with constant velocity.

> No . . . we cannot feel anything if the road is smooth and the vehicle is traveling in a perfect straight line.

Yet, this type of reasoning was strongly tied to that particular context, namely, "the feeling of something" when inside a non-accelerating vehicle, and was not used in other contexts, like those used in the present study.

It should be also mentioned that three students thought of performing an experiment (dropping a coin, or performing a standing vertical jump) in order to ascertain the vehicle's uniform straight line motion. But all three employed perception and concluded that whatever is in the air, whether a coin or their own body, will land at point that is different from what it would be if the vehicle were at rest, thus giving in advance the response to the problem tasks that were to follow the clinical interview.

> If we dropped a coin . . . we could see where it would land. . . . If it landed behind me then I could say that I am in motion.

> I could jump and watch where I would land. If the vehicle is in motion . . . I will land either to the left or to the right . . . because while I'm in the air the vehicle has moved.

In short, students relied heavily on perception, which in turn provides strong evidence that they did not have the conception of the equivalence between rest and uniform straight line motion.

Further evidence was also provided by the students' responses to the problem tasks, particularly the first task of the first category. Only one student could think that both people standing on either end of the car compartment of a train could catch the ball simultaneously, as they would if the train were at rest. This finding reconfirms the results of Lie's (1985) and Whitaker's (1983) studies. As has been cited in the review of the literature, the former found that the length of a standing broad-jump performed by a person in the compartment of a train is thought to be dependent on the direction of the jump--being longer if the person jumps in the same direction as that of the motion of the train. The latter reports that students thought that a bolt falling from the ceiling of the car compartment of a train that is moving with constant velocity will not move in straight line but rather in a parabola due to the motion of the train.

The Concept of Relativity of Motion

Another fundamental concept of the Newtonian model of motion is that of relativity; motion as well as the laws that describe it are defined relative to an inertial frame of reference. An inertial frame of reference is a frame of reference moving with constant speed in straight line; therefore it should be considered as any system on which the laws of motion are applicable, in the same way as if the system were at rest. It is quite apparent that the notion of relativity and that of the equivalence between rest and uniform straight line motion are inter-related. Yet, an assessment of whether or not students have an understanding of the concept of relativity of motion allows for an evaluation of the preferred frame of reference in the students' thinking.

From the clinical interview it became evident that all students had the conception that motion is defined relative to an "observation point"--not frame of reference--such as a point on the ground or another object which we consider to be at rest. (Students were asked to imagine themselves onboard an aircraft, and determine whether they are in motion. They could also see another airplane that appeared to be at rest relative to them.) Moreover, several students used expressions such as "that's how I perceive it," "that's how I see it," and "that's how it appears to me," thus providing evidence that motion is observed from a reference point. The following excerpts represent the thinking of five students:

> You mean I can see an airplane in the sky? . . . Well it appears to be at rest but it's not . . . we know it is moving. . . . The only thing we can do is find something that is at rest . . . the ground . . . a star.
>
> I see the aiplane in the sky . . . to me it appears to be at rest . . . it's like an illusion, because the airplane is moving relative to the ground.
>
> If I see another plane in the sky that appears to be at rest . . . then to me that airplane is at rest, but it is moving relative to someone on the ground. . . . We are both right . . . only the guy on the ground sees the real motion of the airplane.
>
> You mean how I see it? Well, when I'm inside the airplane and I don't feel anything . . . I have to look down and see the ground . . . so motion is relative to the ground. . . . It could be relative to the airplane but it's more, I would say, convenient to take the ground as our reference point.
>
> Motion is not relative to the airplane that I'm seeing in the sky because to me that airplane appears to be at rest. . . . Always we have to find something that is not moving.

Although the above responses provide a commonsense way of approaching motion, they nonetheless provide evidence that the preferred frame of reference is "terra firma." A few students, of course, when asked, gave the train as a reference frame; but their reasoning strategy, namely, that the ball and the train "move towards each other" (Task 1), or that the ball and the train "move away from each other," the former going up, while the latter moving forward (Task

4), made it apparent that motion was observed from the ground. Additional evidence for this preference is provided by the fact that, although two persons (one onboard a moving train and one standing on the platform, as well as one running and another one standing still in the rain) can describe motion according to their own point of view (both persons are right in describing paths and velocities of moving objects), a realist perspective was predominant in all students. For they all responded that the real direction of the raindrops or of a coin flipped inside the car compartment of a train is that perceived by the person who is standing still on the ground. However, in the situation of a person standing still and another one running in the rain, several students (ten) appeared to adopt a point of view from the fixed stars thus giving a metaphysical realist belief. Two of those 10 students said:

> The real direction of the rain is vertical . . . this is what the person standing still sees but . . . it is also the direction of the raindrops if we look from outside the earth.
>
> We have to look at the earth from space if we want to see real direction of the rain.

Their responses to the particular problem tasks further verified the fact that motion is approached from an absolute point of view, that is, from a point of view from the ground or the fixed stars.

Only three students talked explicitly about frame of reference. Yet, for all students, the notions that motion is defined relative to a reference--or rather observation--point and/or relative to a frame of reference appeared to be strongly dependent upon the context of the problem situation. Even those three students who seemed to have an understanding of the concept of relativity thought that motion is relative to the frame of reference (train) only when motion takes place inside the compartment as in the case of Tasks 2 and 4 (see Tables 1, 2, 3 and 4 in Chapter IV and Table 12 in the section of Strategies and Preconceptions in this Chapter). Some other students approached motion relative to the train (although this was not made explicit but was rather inferred from their thinking strategy) but only when the motion of the object was in the vertical direction (Task 4), when the object was moving "inside" the frame of reference (Task 2), and when it was in contact with the frame of reference (Task 4). For those particular students, the notion of relativity was intuitive, as this is discussed in the section of preconceptions. On the other hand most of the students who used the train or the ground as a frame of reference, explicitly or implicitly, reasoned that motion should be viewed relative to the stars when the motion of an object projected vertically from the ground was instead considered. This suggests that always something that is considered to be at rest must be established and then motion will be viewed relative to it.

It deserves to be mentioned that the responses to the problem task of a cannon ball fired straight up in the air make it quite evident that the supposedly simple notion of an earth moving with a constant velocity poses tremendous conceptual problems that are similar to those experienced by scholars and philosophers in the 16th and 17th century Europe. Even the two students who thought that the cannon ball will fall straight back down, since "this situation is similar to that of a person throwing a softball from the roof of a train," adopted an observation point on the fixed stars from which they could describe the parabolic path of the cannon ball. Yet, this reasoning strategy, although not incorrect, does show that the idea that motion is relative to an inertial frame of reference is difficult for students to grasp unless it is taught to them explicitly.

In summary, the majority of students showed a preference for defining motion relative to a point either on the ground or on the fixed stars. Although a point of reference is not the same thing as a frame of reference, the preference for the ground or the fixed stars as an implicit point of observation suggests that the concept of frame of reference was not understood. This preference for an absolute frame of reference is in agreement with findings of previous studies which have been discussed in the review of the literature (Aguirre, 1988; Aguirre & Erickson, 1983; Saltiel & Malgrange, 1980, Whitaker, 1983).

The Conceptual Link between Zero Net Force and Uniform Straight Line Motion

The fundamental idea that motion with constant velocity takes place in the absence of a net force was understood by three students as this appears from the consistency with which they thought about the various problem tasks. But only one student had a higher level of understanding since he used the same reasoning strategy, namely, that the net force on any body moving in straight line with constant speed is zero, across all contexts (see Table 11 and responses to tasks of category 3 in Chapter IV).

From the preliminary interview it became evident that most students could correctly predict eternal uniform straight line motion in the absence of external forces. These students could reason that a spaceship, once set in motion, can move even with its engine off since it is carried by its initial momentum that remains constant, provided that there are no forces to slow the spaceship down. And they also thought that a spaceship already traveling with constant velocity is not acted upon by a force. However, as the context began to change so did the thinking of the students. As was already mentioned, it was only three students who had the conceptual link between zero force and motion at constant velocity. For the great majority of students uniform straight line motion and force in the direction of motion were two concepts that could exist in their minds without any contradiction. The co-existence of a net force and constant velocity in the minds of students is in line with previous findings (Halloun & Hestenes, 1985a, 1985b).

Strategies and Preconceptions

The purpose of any study on how students think is first to identify and describe the strategies that students employ. These strategies are rather explicit, and are directly revealed through the responses. The second step is to identify and describe the preconceptions that lead students to adopt their strategies. The preconceptions are rather implicit, and an inference based upon further questioning about other related concepts, such as frame of reference, acting forces, and path of the moving object is made. Sometimes it might be necessary that students become aware of their change in reasoning strategy through a comparison between their responses to similar or different problem tasks. In such cases the students make their preconceptions explicit. For example, the comparison between the problem situation of a ball thrown upwards from the roof of the train (Task 5) and that of a ball thrown up from the floor of the train (Task 4) made some students state explicitly that "objects moving outside the train are not in the frame of reference."

But it is also possible that a preconception could be directly inferred from the reasoning strategy. For example, the "meeting of two objects" moving in the horizontal direction (such as the ball and the train in Task 1) implies a preference for a reference point on the ground. This preference, in turn, suggests the preconception that motion is observed from the ground.

Although strategies and preconceptions are intricately related, and it therefore remains a mere speculation which gives rise to which, a linear model (see Figure 24 in Chapter III) that postulates a distinction between these two is a convenient way to both identify and descibe them. From the analysis of the individual responses the strategies that students employed while thinking about the problem tasks could be identified. Although students used with some consistency the same strategy while thinking about particular problem tasks (for example, most students employed perception and approached motion relative to the ground in Tasks 1 and 2, while two students used vector composition of velocities in the same tasks and one of them also used it in Task 8), the responses, when considered across all contexts, did reveal that the same problem situation results from different strategies that are dependent upon the context in which the problem is set. In short, the same students changed their strategies according to the context (see Tables 12, 13, 14, and 15).

Table 12

Reasoning Strategies and Preconceptions for Problem Situation of Two Persons Standing On Either End of Car Compartment of Train and Throwing or Rolling To Each Other the Ball They are Each Holding

TASK	STRATEGY	PRECONCEPTION
1	(a) Motion relative to the frame of reference (*n* = 1)	
	(b) Motion of two bodies (ball, train) relative to the ground and meeting each other (*n* = 17)	Motion is observed from the ground (*n* = 17)
	(c) Vector composition of velocities (ball, train) without reference to distances traveled (*n* = 2)	Motion is observed from the ground (*n* = 2)
2	(a) Motion relative to the frame of reference (*n* = 3)	
	(b) Motion of two bodies (ball, train) relative to the ground and meeting each other (*n* = 11)	Motion is observed from the ground (*n* = 11)
	(c) Vector composition of velocities without reference to distances traveled (*n* = 2)	Motion is observed from the ground (*n* = 2)

(table continues)

TASK	STRATEGY	PRECONCEPTION
	(d) Motion inside the atmosphere of the train that "carries" the ball (n = 2)	Frames of reference have an atmosphere (n = 2)
	(e) Motion relative to the train due to its "closedness" (n = 2)	Frames of reference are closed vehicles (n = 2)
3	(a) Motion relative to the frame of reference (n = 3)	
	(b) Motion of two bodies (ball, train) relative to the ground without reference to speeds and distances traveled (n = 12)	Motion is observed from the ground (n = 12)
	(c) Motion relative to the train that "carries" the ball (n = 5)	Objects belong in the frame of reference only when they are in contact with it (n = 5)

Table 13

Reasoning Strategies and Preconceptions for Problem Situation of Person Throwing a Ball Straight Up From Car Compartment of Train, and when Running on Flat Ground

TASK	STRATEGY	PRECONCEPTION
4	(a) Motion relative to the frame of reference (*n* = 3)	
	(b) Motion of two bodies (ball, train) relative to the ground that move in different directions and away from each other (*n* = 5)	Motion is observed from the ground (*n* = 5)
		The observer on the train sees a straight line path of an object thrown straight up while the observer on the ground sees a curved path (*n* = 3)
		The observer on the train sees a curved path of an object thrown straight up while the observer on the ground sees a straight line path (*n* = 2)
	(c) Forward motion of ball relative to the ground as the ball is going up and down in the air (*n* = 12)	Objects continue to move in the forward direction once they are thrown up in the air because there is a force supplied by the motion of the train (*n* = 7)

(table continues)

TASK	STRATEGY	PRECONCEPTION
5	(a) Forward motion of ball relative to the ground as the ball is going up and down in the air (n = 5)	Motion is observed from the ground (n = 5) Objects continue to move in the forward direction once they are thrown up in the air because there is a force supplied by the motion of the train (n = 3)
	(b) Motion of two bodies (ball, train) relative to the ground that move in different directions and away from each other (n = 15)	Motion is observed from the ground (n = 10) Frames of reference are closed vehicles (n = 5)
6	(a) Motion relative to the frame of reference (n = 1)	
	(b) Motion of two bodies (ball, human body) moving in different directions away from each other (n = 19)	Motion is observed from the ground (n = 14) The human body is not a frame of reference (n = 5)

Table 14

Reasoning Strategies and Preconceptions for Problem Situation of Motion of Body Thrown or Projected Straight Up in the Air From Ground

TASK	STRATEGY	PRECONCEPTION
7	(a) Motion due to the vertical component of velocity (n = 20)	
8	(a) Motion of cannon ball relative to space by considering the ball's forward velocity as it is going up and down in the air due to the earth's forward motion (n = 2)	Motion is observed from the fixed stars (n = 2)
	(b) Motion of two bodies (cannon ball, earth) relative to space that move in different directions and away from each other (n = 17)	Motion is observed from the fixed stars (n = 17)
	(c) Vector composition of velocities (cannon ball, earth) without reference to distances traveled (n = 1)	Motion is observed from the fixed stars (n = 1)

(table continues)

TASK	STRATEGY	PRECONCEPTION
9	(a) Motion of two bodies (rocket, earth) relative to space that move in different directions and away from each other (n = 18)	Motion is observed from the fixed stars (n = 18) An object thrown up from the frame of reference does not belong in the frame of reference because it is "moving away" from it (n = 3)
	(b) Motion of rocket relative to space by considering the rocket's forward velocity as the rocket is going up and down (n = 2)	Motion is observed from the fixed stars (n = 2)
10	(a) Motion of two bodies (air-balloon, earth) relative to space that move in different directions and away from each other (n = 17)	Motion is observed from the fixed stars (n = 17)
	(b) Motion of air-balloon inside the earth's atmosphere that "carries" it along (n = 3)	An object rising straight up from the ground belongs in the frame of reference of the earth because the object is moving inside the earth's atmosphere (n = 3)

Table 15

Reasoning Strategies and Preconceptions for Problem Situation of Motion of Two Bodies Moving Along the Equator in Opposite Directions Around the Earth

TASK	STRATEGY	PRECONCEPTION
14	(a) Motion of boats relative to the frame of reference of the earth ($\underline{n}$ = 4)	An object in contact with the frame of reference belongs in the frame of reference ($\underline{n}$ = 2)
	(b) Motion of boats relative to space without reference to distances traveled ($\underline{n}$ = 16)	Motion is observed from the fixed stars ($\underline{n}$ = 16)
15	(a) Motion of airplanes relative to space without reference to distances traveled ($\underline{n}$ = 20)	Motion is observed from the fixed stars ($\underline{n}$ =20)

Evidence that context plays a major role in the students' reasoning process can be seen in the thinking of three students who consistently used the concept of "frame of reference" and approached motion relative to the train in contexts involving the motion of a ball "inside" a train, regardless of the direction of the motion of the ball, and regardless of whether the ball is moving in the air or rolling on the floor (see Tasks 2, 3, and 4, and Tables 12 and 13). Yet those same students did consider the motion of the ball when thrown from the roof of a train or by a running person relative to the ground (see Tasks 5 and 6, and Table 13). It is worth mentioning that, although those three students did not see any difference between the situation of a ball thrown upwards by a person standing inside the car compartment of a moving train and that of a ball thrown upwards by a person standing on the roof of a train, they nonetheless "felt," or had the intuition, that something is different.

In the context of the running person the students explicitly said that "things are different." Even that student who correctly thought about the problem tasks involving the motion of the ball inside and outside the train (Tasks 1, 2, 3, 4, and 5) approached motion relative to the ground in the context of the running person (see Task 6 and Table 13). And the only student who responded that the ball should come straight down to the person's hand, did so because he did not want to contradict himself. For if that were the case, he should have reconsidered everything that he had said about the rest of the problem tasks.

Another good illustration of the effect of context can be seen in the problem situation involving the motion of an object that is thrown up or projected from the ground (see Tasks 7, 8, and 9, and Table 14). A unanimous response to the problem situation involving a person throwing a rock straight up in the air was that the rock always comes back straight down. And the accepted explanation that the person imparts only an upward velocity and not a horizontal one was given almost intuitively.

The same unanimous response was given to the problem situation of a cannon ball fired straight up in the air. Yet, a disequilibration began to take place when the students were reminded that the earth is also moving. Many of them began to reconsider their previous ideas:

> Oh, yes, the rock doesn't go very high . . . the cannon ball shouldn't return to the same point, because the earth has moved.
>
> The rock I'm throwing up in the air will not fall straight back to my hands because the earth is always in motion. But we cannot feel this motion, and that's why the rock will always fall in my hands.
>
> The stone comes straight down because it doesn't go high up, but the rocket goes very high, and in the meantime the earth has moved.

All of the students began to have second thoughts about whether a cannon ball or rocket will return to the same point on the ground on their way back down to the earth. It is very interesting to note how the 100% certainty in the context of a rock thrown up in the air changes into 100% uncertainty in the case of a rocket.

Although all tasks in the first two categories were essentially concerned with the same problem situation, that is, the motion of an object in an inertial frame of reference (train and earth), and the tasks of the third category with the identification of a net force on a body traveling with constant velocity, all students did respond by considering other irrelevant (from a Newtonian point of view) to the problem concepts. This also reconfirmed the fact that students construct knowledge by putting into relationship all the possible factors that might be involved in a given problem situation.

The evidence provided by the thinking patterns of students strongly supports the premise of Phenomenography (Bowden et al., 1992; Marton, 1986), namely, that people understand each phenomenon in a number of ways. In looking at Tables 12, 13, 14, 15, and 16 one can see how strategies changed from task to task. The preconceptions for each strategy are also shown. The most common preconceptions are now discussed.

Preconception 1: Motion Is Observed From A Point Considered At Rest Relative To The Surroundings

For all students, including those who explicitly used the notion of frame of reference in some contexts, motion was also viewed from a point either on the ground or on the fixed stars in other contexts. It is quite interesting to note that even those students who had consistently used the ground as their frame of reference both in the context of the motion of the ball inside and outside the train (see Tasks 1, 2, 3, 4, and 5, and Tables 1, 2, 3, and 4 in Chapter IV, and Tables 12 and 13 in this Chapter) and in the context of the firing of the cannon ball and the projection of the rocket (see Tasks 8 and 9, and Tables 6 and 7 in

Chapter IV, and Table 14 in this Chapter) "observed" motion from a point on the fixed stars in the context of the sailing of the boats and flying of the airplanes around the earth (see Tasks 14 and 15, and Tables 8 and 9 in Chapter IV, and Table 15 in this Chapter). When asked about what was the frame of reference in the latter case all those students thought that it should be "the space" or "something outside." And when they were requested to compare the situations of the firing of the cannon ball and the projection of the rocket with those of the sailing of the boats and the flying of the airplanes around the earth, most students reasoned that "the frame of reference changes" or that "it is easier or more convenient to see it from space," while two students characteristically said:

> When I'm on the ground I can see where the cannon ball or rocket falls . . . I can stay near the cannon and watch the cannon ball land farther to the left. . . But I must be outside the earth if I want to see the boats or the planes go around it.

> We must move outside the frame of reference [earth] if we want to see the whole thing.

Another point worth mentioning and which is consistent with the view that motion is observed from a point is that many students used the notion of the "person" on the frame of reference as the frame of reference. Evidence for this anthropomorphic conception of the frame of reference is also provided by the "me" as a frame of reference in several contexts.

<u>Preconception 2: Motion Is Considered Relative To The Frame of Reference When Motion Takes Place Inside The Frame of Reference</u>

It made a difference in the thinking of most students whether the body is moving inside or outside a moving vehicle. "Moving inside" was associated with motion relative to the vehicle, while "moving outside" was associated with motion relative to the ground or the stars. Lie (1985) found the same preconception.

It is quite interesting to note the difference in the responses, and, of course, the reasoning patterns of the same students. For although only one student thought that simultaneity is possible in the situation of the two balls moving outside along the roof of the compartment of the train (see Task 1 and Tables 1 and 2 in Chapter IV, and Table 12 in this Chapter), the idea that the balls can be caught simultaneously when the two people are inside a moving train was much more frequent (see Task 2 and Tables 1 and 2 in Chapter IV). Four students thought as follows:

> One guy will catch the ball first because he is moving towards the ball. But inside the train, I don't know, I think I'm confused now.

> When you are outside, the frame of reference is the earth, therefore the guy in the back of the train will catch the ball first because the ball travels a shorter distance. But inside the train, the frame of reference is the train, so both guys should catch it at the same time. Well, I think . . . yes, I'm sure both guys will catch it at the same time.

> Well, when you are inside the train things should be different; because the air is moving.

> There is a difference when you are inside because everything is moving with the train. Everything is part of the frame of reference.

Preconception 3: Motion Is Considered Relative To The Frame Of Reference Due To The Atmosphere Inside The Frame Of Reference

It made a difference in the thinking of two students whether the object in motion is inside the "air" or "atmosphere" of the train (see Task 2 and Table 1 and 2 in Chapter IV). For "if the air where pumped out of the car compartment of the train" things would be different "because the frame of reference would change." Or, as the other student thought, "when there is air inside the train we can define a frame of reference; but with no air, the frame of reference becomes the earth." Although both students reasoned that if there were no air inside the compartment of the train the person in the back would catch the ball first because "he is moving towards the ball" (thus adopting the ground as their reference point and using perception like the majority of the students), the idea that the existence of an atmosphere implies the establishment of a frame of reference cannot be dismissed.

However, the notion of atmosphere was invoked by another three students in the context of the rising of an air balloon (see Task 10 and Tables 6 and 7 in Chapter IV). When those three students were asked to compare the motion of a cannon-ball with that of an air balloon they explicitly spoke of the velocity of the balloon (it is not as great as that of the cannon ball) as well as of the fact that "an air balloon is rising" while "a cannon ball is fired." And one student (of those three) who had previously thought that a cannon ball or rocket should return to the same point because the situation is similar to the one involving a ball thrown straight up from a moving train, did not think in a similar manner in the context of the air balloon. For as he stated, "the air balloon returns to the same point because as it's going up in the air, the atmosphere pushes it along." This provides additional confirmation of the primacy of the context over the universality of the laws of motion!

Another interesting point is that those three students who used the notion of atmosphere to predict the motion of the air balloon adopted the earth as a frame of reference. Although this adoption does not provide evidence for an understanding of the concept "frame of reference," it does show that the students' "observation point" was on the earth. All three students did believe and explain that "we can stay above the same place if there are no strong winds," and that by going very high in a hot-air balloon, they could not land in a different place, as the rest of the students thought, despite the fact that one of them had his reservations:

> But this way of travelling would be very tiring and dangerous too. . . . The crossing of the Atlantic would require many hours . . . and we never know where we will land because there are strong air currents over

> the Atlantic. And the earth moves from west to east, so we could only go west. But still, it can be very dangerous. . . . Oh, you said we neglect wind. Then I suppose it would take many hours. . .oh, yes, it takes only 24 hours for a complete rotation...so it wouldn't take that long. . . but . . . I think we don't do this kind of travelling because we cannot neglect the wind. But as the earth spins it creates a wind. . . air currents.

However, what is interesting is the fact that all three students agreed that "if there were no atmosphere the balloon would never return to the same point." And two of them also changed the frame of reference, or rather the observation point, since perception became their thinking strategy thus viewing the motion of two objects--the earth and the balloon--relative to the fixed stars.

<u>Preconception 4: Motion Is Considered Relative To The Frame Of Reference When The Moving Body Is In Contact With The Frame Of Reference</u>

It made a difference whether the balls are moving in the air or whether they are rolling on the floor of the compartment of the train (see Table 12 in this Chapter). For five students the rolling of the balls (see Task 3 and Tables 1 and 2 in Chapter IV, and Table 12 in this Chapter) implied that motion should be considered relative to the train because "the balls are part of the motion of the train", or "the balls are traveling the same distances." And two of those five students used the same strategy in the context of two boats sailing around the earth (see Task 14 and Tables 9 and 10 in Chapter IV, and Table 15). And in the case of the two planes flying around the earth all

20 students thought that one plane should arrive first at the point from which the planes took off (see Task 15 and the same Tables as above).

It is quite interesting to be mentioned in passing that even those two students who appeared to have the concepts of relativity and frame of reference, since they used those concepts with consistency both in the context of the ball moving inside the train (Tasks 2, 3, 4, and 5) and the boats sailing around the earth (Task 14), did not used the earth as a frame of reference. For they thought that "the airplanes are not on the earth any more." In their phenomenographic study, Bowden et al. (1992) have also identified a category of this type of student reasoning.

Preconception 5: Motion Is Considered Relative To The Frame Of Reference When The Body Is Moving Towards The Frame Of Reference

It made a considerable difference in the thinking of students whether an object is projected upwards from the ground or whether it is dropped from a height to the ground. For although 18 students approached motion from an absolute point of view and thought that a rocket cannot return to the same point on the ground (see Task 9 and Table 6 in Chapter IV, and Table 14), 13 students did think, by viewing motion as being relative to the ground or the stars, that an iron ball will hit the ground at a point that is directly under the point of release (see responses to Task 13 in Chapter IV). Another interpretation of the responses to Tasks 9 and 13 is also given in the section of Knowledge Representation.

Preconception 6: Two Observers See Different Events

For some students a person on the train and a person on the ground see, not only different paths and velocities of the ball thrown straight up in the air (see Table 13), but also different events taking place since the former sees the ball coming straight down to his/her hands, while the latter sees the ball landing behind him/herself. And the opposite is also true. One student, in fact, gave a very rational explanation, which, however, shows the effect, and at the same time the limitation, of analogies on understanding abstract concepts.

> It's like the two people, one standing and the other running in the rain. The one standing still sees the raindrops falling straight down . . . if he holds the umbrella straight up. But to the other guy who's running the raindrops appear to be coming at an angle . . . they see different things . . . they are both right, but this is how they perceive it . . . and one will be soaked to the skin even if he's running with an umbrella in his hand, unless he changes the direction of the umbrella. . . . So they see different paths, one straight, vertical, and one at an angle . . . and the guy standing still will be dry . . . and the other one will be wet in the front, unless like I said he turns his umbrella like that.

Preconception 7: Uniform Straight Line Motion Is The Result Of The Interaction Between Two Opposing Forces Of Different Magnitude

It makes a difference whether an object is moving away from any interactions, as in the case of a spaceship traveling in outer space (see responses to Task 16 in Chapter IV and Table 16 below), or whether it is moving under the influence of two forces of which one is opposing the object's motion, as in the case of car traveling on a windy day or a box being pushed along the floor (see responses to Tasks 17 and 20 in Chapter IV). One student said:

> When I'm pushing the box the force I'm applying must be greater than the force of friction. On the spaceship there are no forces . . . it (the spaceship) is moving because it has a momentum that was given by the engine . . . it will move forever unless there are forces to slow it down. . . . If there is a force in the opposite direction, the force from the engine must overcome this force. . . a force must be supplied continuously, otherwise the spaceship would slow down.

Is is very interesting to be mentioned that, although the preconception that motion with constant velocity implies a net force began to surface in the context of a moving car, the preconception that an object can move with constant speed only in the absence of resistive forces were identified when students were questioned about the initial problem task with the spaceship, to which they had apparently given the accepted Newtonian response.

> I don't see any difference between the spaceship, the car, and the box, if the spaceship is moving inside an atmosphere.

> There is no net force on the spaceship . . . it just moves . . . it is carried . . . because there was a force that set it in motion . . . (this) force acted for a very short time. . . . we are in outer space, but if there are forces in the opposite direction . . . then there must be a force in the forward direction.

> You asked me about the force on the spaceship. . . . If you told me that the spaceship has to overcome friction . . . I think the net force on the spaceship is the force applied by the engine and the force of friction . . . yes like the car moving on the road.

This type of reasoning provides evidence that motion is viewed as the result of two competing forces even when the problem situation explicitly states that the object in question is moving with constant velocity. Halloun and Hestenes (1985a) reported identical findings.

<u>Preconception 8: Motion Of Objects In The Forward Direction Once They Are Thrown Up In The Air From A Frame Of Reference Is Due To A Force Supplied By The Motion Of The Frame Of Reference</u>

Seven students believed that a softball, once thrown up in the air by a person standing on the floor of moving train (see Table 13), will continue to move forward while it is also moving up and down in the air (inside the car compartment), because there is a force supplied by the train.

> It is the force of the train . . . because the train is moving.
>
> We know that whatever we throw up . . . falls back down to our hand. . . . If there is no force on the ball while it's going up in the air it will land behind.
>
> Motion without a force? I mean, there has to be a force, otherwise everything would hit the back of the train . . . this doesn't happen.

Three of those seven students also entertain the same preconception in the context of the motion of the softball thrown up in the air from the roof (outside) of the train.

Table 16

Reasoning Strategies and Preconceptions for Problem Situation of Object Moving with Constant Velocity

TASK	STRATEGY	PRECONCEPTION
16	(a) Linking net force to constant velocity ($\underline{n}$ = 8)	There is a force in the direction of the spaceship's motion because the spaceship is in motion ($\underline{n}$ = 4)
		Objects in motion are acted upon by a continuous force because the force that sets objects in motion has a limited range of action ($\underline{n}$ = 3)
		Forces producing acceleration have an increasing magnitude ($\underline{n}$ = 6)
		A spaceship can move with constant velocity because the force supplied by the propulsion engine is applied in short bursts ($\underline{n}$ = 4)
		There are forces producing acceleration and those maintaining constant velocity ($\underline{n}$ = 4)

(table continues)

TASK	STRATEGY	PRECONCEPTION
	(b) Linking zero net force to constant velocity (n = 12)	An object can move in the absence of a net force only if it is set in motion and there are no forces to slow it down (n = 6)
17	(a) Linking the resultant of the forces exerted by the engine and the wind to constant velocity (n = 16)	The force exerted from the engine is greater than the force exerted by the wind (n = 16)
		There is a force in the direction of the object's motion resulting from one accelerating force and one decelerating force (n = 4)
	(b) Linking zero net force to constant velocity (n = 4)	
18	(a) Linking net force to motion along an incline (n = 17)	Motion along an an incline is due to two forces of different magnitude (n = 17)
	(b) Linking zero net force to constant velocity (n = 3)	

(table continues)

TASK	STRATEGY	PRECONCEPTION
19	(a) Linking greater net force to the motion of an object with greater mass (n = 19) (b) Linking zero net force to constant velocity (n = 1)	Objects with greater mass are acted upon by greater force (n = 19)
20	(a) Linking the resultant of the force exerted by the person and the force of friction to constant velocity (n = 17) (b) Linking zero net force to constant velocity (n = 3)	The force by the person is greater than the force of friction (n = 17)

Some Comments On Preconceptions

Explanations about why a particular student has thought about a particular problem task the way he or she has are usually taken to be mere speculations. Why, for example, did the two students who used vector composition of velocities in Tasks 1 and 2--incorrectly though since they did not take into account the different distances covered by the two balls--not use this same strategy in the context of the two balls rolling on the floor of the compartment of the train (Task 3)? Why did only one of these two students use vector composition of velocities to predict the motion of a cannon-ball (Task 8)? Why did the two students who invoked the notion of atmosphere to predict the motion of the balls inside the train (Task 2) not use the same notion in the context of the rising balloon (Task 15) given the fact that the notion was invoked by three other students? And why did that same student who had supposedly used with consistency the same strategy across three contexts not use vector composition in the context of the rocket (Task 9)? From a pedagogical point of view, however, it would be more appropriate to make a number of general points regarding preconceptions than concentrate on providing explanations about why or how these preconceptions have been developed.

The Contextual nature of preconceptions. Like reasoning strategies, preconceptions are contextual since, for example, only two, of those five students who used "contact" as a criterion for judging whether or not an object belongs to the frame of reference (Task 3), thought that the boats (Task 14) move relative to the earth. The notion of "atmosphere" was invoked by two students in the context of the motion of a ball inside the car compartment of a train (Task 2), but not in the context of the rising air balloon (Task 10). Instead, three other students made reference to "atmosphere" in the latter context.

The inter-relationship of preconceptions. Preconceptions are inter-related and a certain response could very well result from more than one preconception. Five students, for example, thought that once a ball is thrown straight up in the air by a person standing on the roof of the moving train the ball will land behind the person because "the ball is outside the frame of reference" while two had also the preconception that "there is no force acting in the forward direction because the ball is not moving inside the train." However, it should be stressed that for each problem task there was a primary preconception that led students to reason the way they did, and secondary preconceptions were identified upon further questioning.

The latent nature of preconceptions. Preconceptions do not become evident from the responses. Preconceptions are inferred either from reasoning strategies or through further questioning about those strategies. Most of the time students were requested to compare and contrast their responses to certain problem tasks. It was after they became aware of their strategies in thinking about problem tasks that preconceptions were identified.

For example, in the case of a rocket fired vertically from the ground (Task 9), the great majority of students used perception as their reasoning strategy, and the preconception that "motion is observed from the fixed stars" was inferred from that strategy and from their response to the question about what was the frame of reference. Yet it was upon further questioning that the preconception "an object moving away from the frame of reference does not belong in the frame of reference" was identified for three students. It was also through further questioning that a preconception about force and motion was identified. For although 12 students thought that a ball, thrown straight up by a person standing in the car compartment of a train, will land in the person's hand because, while the ball is moving up and down in the air, it is also moving forward (Task 4), seven students thought so because they had the preconception that "there is a force acting in the forward direction that carries the ball forward." Similarly, it took students some time beyond the accepted response and the correct strategy, that is, a spaceship is not acted upon by a net force because it is moving with constant velocity (Task 16), to give the preconception that "an object can move with uniform straight line motion only when there are no resistive forces to oppose the object's motion."

Three students who had approached motion relative to the train in contexts involving the motion of a ball inside the train (Tasks 2, 3, and 4), gave the accepted response through an accepted strategy by observing motion from the ground in another context (Task 5). It is obvious that for those three students the preconception of viewing motion from the ground was totally undetected in the context of Tasks 2, 3, and 4.

The implicit and explicit nature of preconceptions. It should be recognized that preconceptions can be implicit or explicit. The idea that motion is observed from the ground or the fixed stars was tacit for some students, while other students explicitly stated their preference for that selection. For example, the three students who changed their point of observation expressed awareness of it. Yet, they could not find an explanation as to why they changed their point of observation when the ball was thrown up from the roof of the train (Task 5). They thought that the path of the ball, once in the air, "should be a curve (parabola) because that's how we see it." They also had a conceptual difficulty with the path of the ball as viewed by a person standing on the roof of the moving train. The same preconception was also had by the two students who employed vector composition in Tasks 1 and 2, and by one of those two students who used in Task 8.

With regard to the nature of preconceptions it should be mentioned that several preconceptions about force were explicit. For when asked about the magnitude of the force acting on a spaceship moving with constant velocity, six students stated that the force is constant because if it were not the spaceship would accelerate. And they went on to identify forces of increasing magnitude as forces producing acceleration, and forces of constant magnitude as forces maintaining constant speed.

Preconceptions vs misconceptions. Preconceptions are not necessarily misconceptions, but instead ideas that are at variance with the scientific ones. For example the preconception that "contact implies that motion is relative to the frame of reference" is not a misconception. Yet it is an idea that is different from the one used by physicists since the latter do not make such a distinction. And the fact that the visual perception of motion is a strategy of the human perceptive system does not make even a perceptual type of thinking a wrong thinking if the strategy is acceptable. Yet "perceptual thinking" is not scientific thinking since a differentiation between a moving vehicle, the ground and the fixed stars is implicitly or explicitly made by the students.

Similarly the preconception "frames of reference are closed vehicles" is not a misconception but rather an incomplete idea, since physicists do not distinguish between "closed" or "open" vehicles. Nor do they differentiate between vehicles and frames of reference, or between vehicles that are "full with air" and vehicles from which air has been pumped out. On the other hand, the idea that there is a net force on a body traveling with constant speed is a misconception since this is an idea that is not only different from the scientific one but is also a wrong one. For there is no net force acting on a body moving with constant velocity. Empirical evidence, either through direct experience or computer simulation, that contradicts the belief in the existence of a net force in the direction of motion can show that this belief is in fact a misconception.

Schematic Representation

From the identification of the strategies and preconceptions an inference about what concepts exist and how they are organized in the students' cognitive structure in regard to their model of motion can be given. This content and its organization is certainly based upon the number of problem tasks used in the present study, and there is the possibility that other concepts might also exist.

The conceptual organization of the student's model of motion is represented by two major types of schemata as shown in Figures 24 and 25. It should be mentioned though that despite the similarities some students' schemata contained more concepts than other students' schemata. In general, however, these two types of schemata provide a comprehensive representation that is particularly useful from a pedagogical point of view when a comparison with the accepted scientific schema (Figure 26) is made.

As can be seen, Figure 24 represents an intuitive schema based upon perception and everyday experiences with motion and forces. This type of schema was employed in the thinking of those students who did not have any understanding of the Newtonian conceptions. On the other hand, Figure 25 represents a schema combining intuitive and scientific concepts. This type of schema contains both the concept of frame of reference and the preconception of motion as observed from a reference point. This inference is based upon the fact that students who used explicitly the term frame of reference and viewed motion relative to that frame of reference--train--also approached motion relative to the ground or the fixed stars in subsequent contexts. In addition, it contains other concepts related to the frame of reference such as "vehicle," "closed," and "atmosphere," since for some students, the concept of frame of reference was linked to a closed vehicle, while for some other students the notion of "atmosphere" was further employed. The notion of being in contact with a vehicle, was also used by some students who intuitively approached motion relative to the frame of reference. Moreover, an intuitive differentiation between two directions of motion, that is horizontal and vertical, was also made. For some students vertical motion, such as that of a ball thrown up by a person standing on the floor of the car compartment of a train, was related to motion relative to the frame of reference, while horizontal motion, as in the case of a ball moving along the length of the train, was approached relative to the ground.

In regard to the causal link between zero net force and motion, there are additional concepts related to that link.

As shown in Figure 25, several students differentiated between "moving" and "resistive" forces, while the magnitude of a force was viewed as being either "constant" or "increasing." Constant magnitude forces were linked to velocity or deceleration, while increasing magnitude forces were associated with acceleration. However, as can be seen in Figure 25, the Newtonian link between constant magnitude forces and acceleration was also present in the schema of some students.

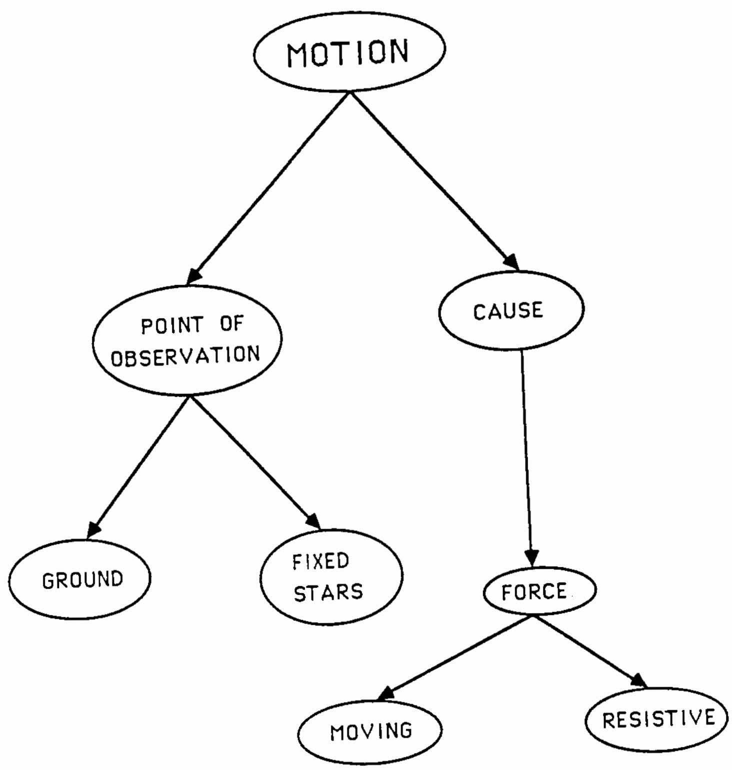


Figure 24. Network Representation of Intuitive Schema of Motion.

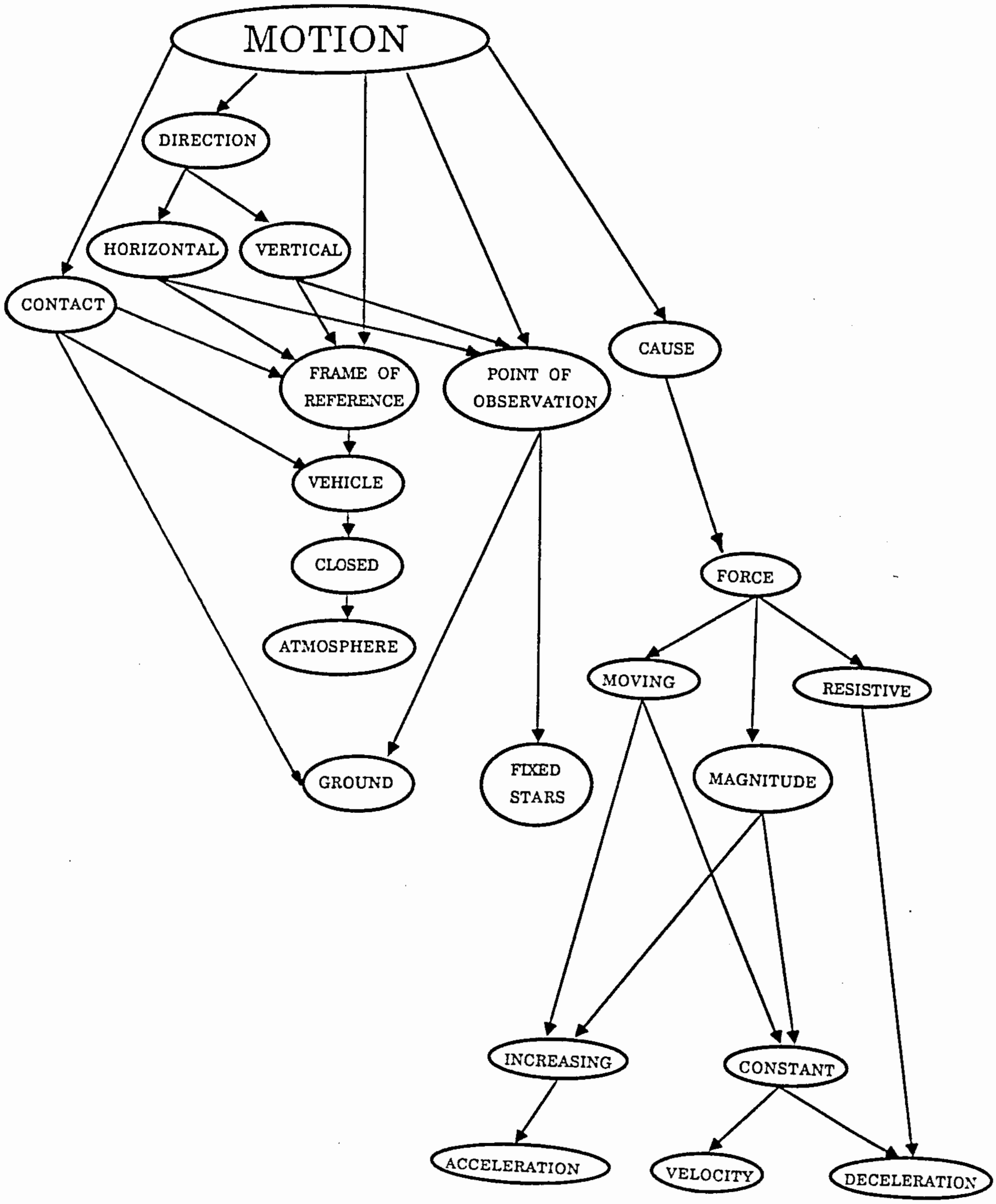


Figure 25. Network Representation of Schema Combining Intuitive and Scientific Concepts.

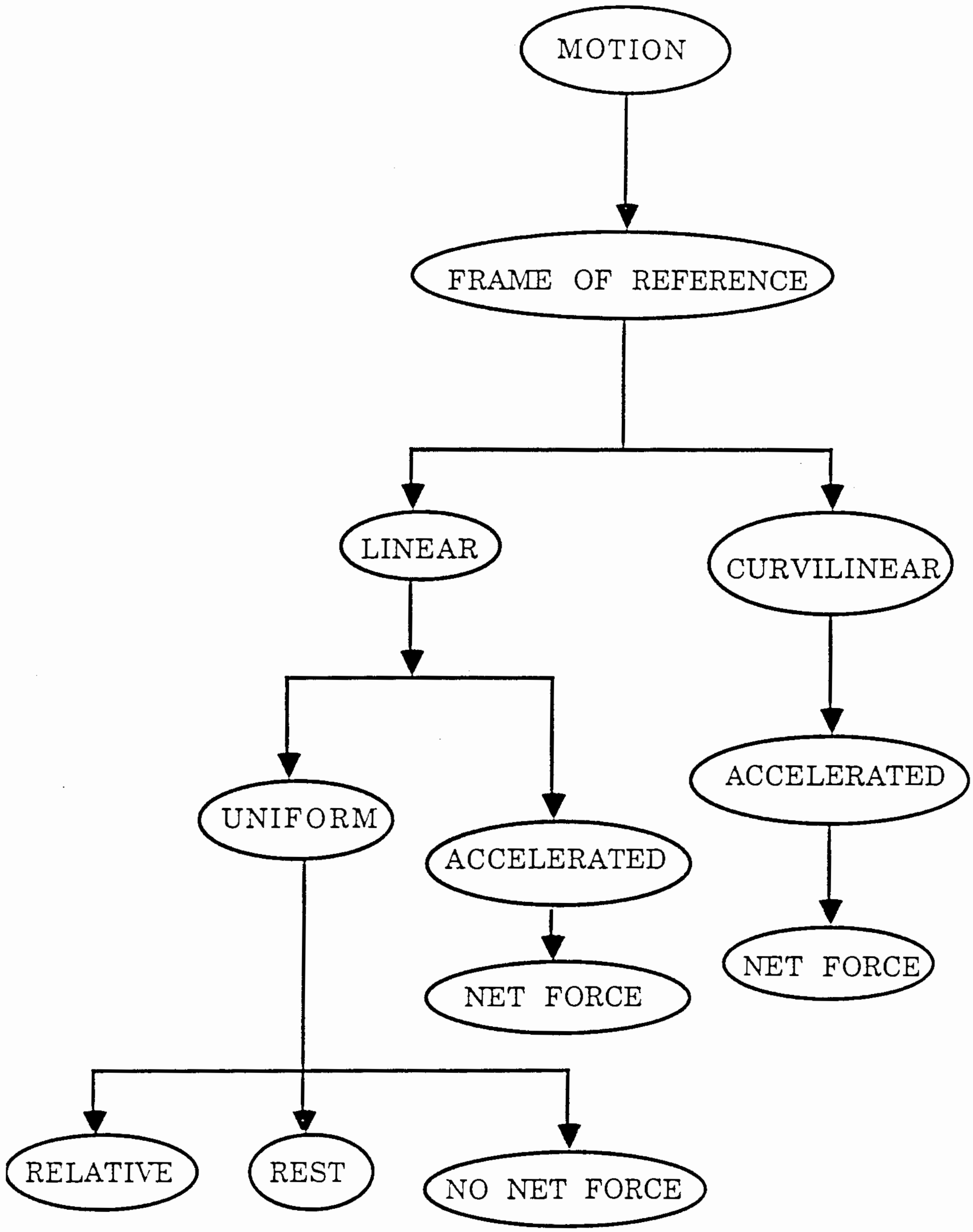


Figure 26. Network Representation of Newtonian Schema of Motion.

Knowledge Representation

With regard to the representational format of the students' knowledge, both propositional and analogical representations seem to exist. Although an interpretation, the reasoning strategies and preconceptions do provide some evidence that the concepts of motion and force are stored not only in a propositional form, and hence in a schematic structure representd by a networks of concepts (Figure 28), but also in an analogical form. And although propositional representations of the concepts of force and motion appeared to exist in all students, the fact that students employed perception suggests that visual images do play an important role in their reasoning process. Moreover, for some students analogical representations were predominant as this became evident from their responses to the task of the motion of a ball thrown upwards from the roof of the train and from the hands of a running person (Tasks 5 and 6) as well as from the responses to the problem situation of string hanging from the roof of a van (Task 21).

In regard to Tasks 5 and 6, students employed visual perception of two separate objects (ball-train, ball-human body) moving in two different directions--the ball moving upwards and the train or human body in the forward direction. However, it was in the case of the ball thrown up in the air by a running person (Task 6) in particular that students provided evidence for the existence of analogical representations. In thinking aloud three students said:

> I'm moving under the ball . . . I have done this . . . I know it.
>
> We are running under the ball . . . it's like the train . . . but I'm not 100% sure. But I'm sure that If I throw a ball while I'm running the ball will land behind me. . . . Look my head is moving under the ball.
>
> I don't know how to explain it, but as you throw the ball up you are moving away from the ball. . . . It's similar to the situation with the guy on the roof of the train, but here you are also involved . . . I mean when you are on the train, you are just moving with the train . . . when you are actually running . . . I think this is a different kind of motion . . . problem . . . now you confuse me.

Even the only student who had the notion that motion is defined relative to a frame of reference (as this became evident from his responses to all five tasks of the first category) thought that

> this case is different because the person is moving under the ball. . . . Here [in the train] the person is also moving under the ball . . . but this is different. I don't know why. . . . But I know . . . and I cannot explain it.

In discussing these responses, it should be pointed out that there is a difference between the visual image of a string hanging straight down from the roof of a van moving in straight line with constant speed (this image has been acquired and retained from personal experiences while inside moving vehicles), and mental images like those of "moving under a ball." For mental images have been acquired not only through visual perception but also through personal experiences with the world. However, as Johnson (1987) argues, these mental images fall in between visual images and abstract propositional structures, and they are therefore partly analogical and are stored in the episodic memory.

Two further points, however, in regard to analogical representations need to be made. The first point is that the present study provides some evidence that visual representations might give rise to propositional representations. For as the majority of the responses to two similar problem tasks demonstrated, an iron ball dropped from the top of a high building would land at the foot of the building, that is, at a point on the ground that was directly under the iron ball at the moment the latter was released (Task 13), while a rocket launched vertically from the ground would not return to the same point on its way back (Task 9). Although for some students the preconceptions of "moving away or towards the ground or frame of reference" was responsible for their response to those two tasks, for other students the visual representation of a building on the ground might have made them established in their mind a local frame of reference and hence treat motion relative to the earth, while in the problem situation with the rocket motion was approached relative to space. This interpretation becomes evident from the responses of some students:

> The iron ball dropped from the building moves in straight line and falls parallel to the building

> . . . it (iron ball) will strike the ground at the foot of the building. . . . The rocket is moving in space . . . away from the earth . . . I may be wrong, but that's how I understand it.

> The building is attached to the earth . . . the building moves with the earth. . . . The rocket is moving alone.

> The earth is moving but the building is also moving with the earth . . . the building is fixed on the earth . . . so the iron ball will land at the foot of the building.

> The earth and the building are moving together . . . they are on the same frame of reference . . . the guy who dropped the ball was on the frame of reference. But the rocket is moving away from the frame of reference.

The second point is that analogical representations are not contextual. This means that, unlike propositional representations, analogical representations are not tied to the context in which the concepts of force and motion are required. For as the thinking of many students about the situation of a spaceship traveling in outer space showed (Task 16), the mental image of "two competing forces" (a moving one and a resistive one), acquired through sensorimotor activities and certainly in contexts that did not involve airplanes (Task 18) and spaceships (Task 16) did in fact guide the reasoning process.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The present study investigated how undergraduate university students who have completed one semester of coursework in non-calculus general physics with elements in Newtonian mechanics understand the Newtonian model of motion. For the evaluation of conceptual understanding paper and pencil tasks in an interview mode were employed throughout the study, while a short clinical interview in the beginning was used to assess prior knowledge such as the concept of relativity, frame of reference, equivalence between motion and rest and Newton's First Law, and contexts in which this knowledge is utilized.

For the construction of the problem tasks two research approaches to assessing conceptual understanding were employed: Phenomenography and Rule Assessment Methodology. The former is based on the philosophical notion that people perceive, conceptualize and understand each phenomenon and concept in a number of qualitatively different ways; the latter is a research methodology based on the idea that people use with consistency a number of reasoning strategies depending upon the context in question, and it is therefore incumbent upon the researcher to identify all possible strategies by constructing contexts in which the same concept is embedded.

The problem tasks were grouped into the following three categories:

1. Motion of an object in a frame of reference.

2. Motion of an object in the frame of reference of the earth.

3. Motion of an object with constant velocity.

The problem tasks assessed the following three fundamental notions of the Newtonian model of motion:

1. Uniform straight line motion is equivalent to rest.

2. Motion in general is relative to an inertial frame of reference.

3. Uniform straight line motion can exist in the absence of a net force.

The responses were analyzed by considering the accepted and the alternative conception(s), and then for each alternative conception reasoning strategies and preconceptions were identified. However, preconceptions were found, even in the accepted conceptions. Finally an inferrence about the schematic representation and about knowledge representation in general was made.

It was confirmed that conceptual understanding is a complex process involving many interrelated factors that depend upon personal experiences and beliefs. There is evidence that the context has primacy over the content since the same concept was understood differently depending upon the context in which the concept was required. There is also strong evidence that in all students' thinking perception played a major role. For in approaching problems involving the motion of an object in a moving frame of reference, all students thought in terms of two separate bodies (the object and the frame of reference) moving relative to each other, but nevertheless viewed motion from their own absolute point of view without reference to the velocities of the objects and the distances they traveled. This "absolute point of observation" was either on the ground or on the fixed stars.

With regard to the schematic representation, two major types of schemata were identified. The first type is an intuitive schema derived from the perception of motion as well as from bodily experiences that suggest a causal link between motion and forces (the moving ones and the resistive ones). This type of schema is a crude one, simplistic, yet convenient and explanatory. The second type of schema is a mixture of the intuitive one and a scientific one. This schema is more complicated with many contradictory concepts which, however, exist in the students' cognitive structure without any contradiction. These findings about the existence of two superimposed schemata without apparent contradiction reconfirm the conclusion of previous studies (di Sessa, 1982; Gilbert et al., 1982; Halloun & Hestenes, 1985a; Reif & Larkin, 1991; Viennot, 1979).

The responses to the various tasks also suggest that the concepts of force and motion are stored not only in the form of propositions, but also in the form of visual images, and mental-image schemata resulting from personal bodily experiences. In short, the concept of force and motion are represented both propositionally and analogically. The first type of schema refers to analogical representations, while the second type is a combination of both analogical and propositional representations. And it deserves to be pointed out that in some students those analogical representations seemed to be much "stronger" than, and remained quite separate from, the propositional ones in certain contexts.

The implications of the existence of those two types of schemata for instructional practices are that the following preconceptions should be the starting point of the learning process if understanding is the goal:

1. Frames of reference are observation points.

2. Frames of reference are closed vehicles.

3. Objects move relative to (move along with) the frame of reference because the objects are moving inside the frame of reference.

4. Objects belong in the frame of reference only when they are in contact with it.

5. Two observers, one on the ground and the other on a frame of reference see not only different paths and

velocities for a moving object, but also different events involving the object.

6. An object dropped from a point high on the frame of reference belongs in the frame of reference because the object is moving towards the frame of reference.

7. An object projected straight up from a frame of reference does not belong in the frame of reference because the object is moving away from it.

8. An object rising straight up from the ground returns to the same point on the ground on its way back down because the object moves along with the atmosphere of the earth.

9. An object continues to move in the forward direction once it is thrown straight up in the air from a frame of reference because there is a forward force supplied by the motion of the frame of reference.

10. An object in motion, including straight line motion, is acted upon by a net force in the direction of motion.

11. A constant force produces constant velocity while an increasing force produces acceleration.

12. The effect of a constant force depends upon its magnitude.

13. An object can move in the absence of a net force only if there are no resistive forces.

14. The net force responsible for the uniform motion of an object results from the interaction of two opposing forces, the accelerating force and the resistive force.

15. An object of greater mass is acted upon by greater net force even when the object is moving with constant velocity.

Conclusion

Students demonstrated an everyday--common sense--understanding based on perception and past experiences with the world. However, they did not have a conceptual understanding of the Newtonian model because they had difficulty in:

1. Treating motion always <u>relative</u> to a frame of reference.
2. Identifying <u>zero net force</u> on an object moving with <u>constant velocity</u> across all contexts.
3. Identifying the equivalence between <u>motion and rest</u>.
4. Using the <u>same concept with consistency</u> in a variety of contexts.

Recommendations

If we, as science educators, take seriously and espouse the shift from behaviourism to cognitive science, then it goes without saying that understanding should be the goal of any science lesson. More than a decade ago, Resnick (1983) made it quite clear that new findings in the area of cognitive science necessitate new approaches to teaching and learning. More than a decade, however, has passed; and, despite the energy, effort, and talent on the part of excellent instructors, "understanding" is seen as a far-fetched dream, let alone a reality in classrooms at both the high school and college level.

True, it took mankind 2000 years to model successfully phenomena of force and motion. It would be therefore paradoxical to expect students to acquire an understanding of the Newtonian model in one or two years, let alone in one semester! It is also true that visual images and the problem of language will always exist--perception is a form of understanding, and motion in everyday language is fundamentally different from rest--and that bodily experiences will inevitably help develop intuitive schemata, and hence "mini theories" and preconceptions about force and motion. However, this type of reasoning does not absolve science educators and instructors from their purpose, that is helping students, at all levels of education, to "truly" understand. But how could they achieve this purpose, given the existence of both intuitive and scientifico-intuitive explanatory schemata, as well as the inevitability of the development and strengthening of those schemata?

Thus far science educators and cognitive scientists have been stressing a number of strategies for helping students understand, and for treating their preconceptions, such as clarification of student ideas at all levels of instruction, challenging these ideas through counter examples, using precise and unambiguous language, differentiating between Newtonian and everyday language, and finally applying a concept in a variety of contexts (Gorsky & Finegold, 1992; Hadzigeorgiou, 1987; Posner et al., 1982, Driver & Oldham, 1986). However, the inevitability of the development of intuitive schemata as well as their persistence into adulthood, point to another alternative avenue. This avenue is the development of a strong scientific schema that can be called upon whenever the situation arises without the constraints imposed on thinking by the intuitive schema.

The development of a strong schema is an idea conceived while conducting the interviews. I noticed quite often that, for the students who had a partial understanding of the Newtonian conceptions, a kind of "intellectual struggle" between the Newtonian conceptions and the intuitive schema was taking place. I therefore postulated that it is the "stronger schema" that determines the final retrieval of concepts, and hence the reasoning strategy employed in a certain problem task. And for almost all students the retrieval took place from the intuitive and not from the scientific, which, as was interpreted, are intermingled. The following specific recommendations could very well show that in the long run (although this will be a matter of another longitudinal study to determine) the only remedy to developing "scientific" understanding is to help students develop the scientific Newtonian schema through a conscious effort on the part of teachers. This approach may very well prove to be more effective and more efficient than the conceptual change approach. These specific recommendations should be seen as steps, taken both jointly and independently, to developing and strengthening the Newtonian schema of motion.

1. Provision of Advance Organizers and Schemata at a Very Early Age

It is my belief that students should be helped to develop the scientific Newtonian schema from early on. It is therefore imperative that a conceptual framework be developed at a very early age, and also strengthened in later years. But not just by teaching the scientific ideas, but rather by providing abstract ideas in a way that could become understood.

Taking into account the shift from the concrete to the abstract, the notion that all knowledge is abstract, and therefore general concepts and ideas that in some way can become understood should be introduced even to young children, appears to be making more sense now than it did ten or twenty years ago. However, it would be totally unrealistic to expect students at the elementary level to understand abstact concepts in a propositional form. For this reason the fundamental ideas should be introduced to students through learning episodes that deliberately contain general ideas. These episodes will serve as advance organizers that will help subsume other less inclusive concepts through progressive differentiation. In addition, the episodes will be remembered due to the "contextual set up." Given the by now famous idea that the most important factor influencing learning is the prior conceptions and experiences of the learner (Ausubel et al., 1978), the utilization of sensorimotor activities becomes justified.

In order for the first law to be introduced through an advance organizer, "action of forces" should be the starting point. An object, like a stone or ball, tied to a piece of string that is twirled around in a circle means action of a force; this is what students, at all levels, feel because it is real. Following this line of reasoning, the advance organizer "circular motion means the action of a force" that can be "felt" by all students can initiate the instructional process. Once this general idea is assimilated, "straight line motion in the absence of a net force" can be subsumed under it. For it would be easier and much more meaningful for students to "see" and "feel" that once they release the string from their hand "the force they were applying becomes zero and the object moves in a straight line." (In addition, this particular advance organizer can help develop at a later stage a meaningful link between circular motion and acceleration.) Given the fact that Newton's First Law, that is motion in the absence of net force, goes contrary to common experiences, then it would make more sense to start from those experiences.

It is not news that the Newton's First Law poses the greatest conceptual problems, since motion in the absence of forces is a utopia and goes contrary to common sense. Yet, activities carefully designed and interpreted could help towards alleviating these problems. Walking, for example, over a trolley-car with constant speed could be used as an organizer that states that "uniform motion in straight line does not involve a net force," since students could "see" and "feel" that, by walking over it, the final displacement of the trolley-car is zero. But as was said, the sensorimotor experiences and their interpretation should be used simultaneously. If these two complementary activities are used at the same time, even the fundamental, but so difficult to grasp, notion that "rest and uniform straight line motion are equivalent," could be understood. For once students are encouraged to imagine themselves inside the car compartment of a train and predict in which direction their standing broad jump would be longer, while, at the same time, performing "live" the same jump inside the classroom, in all possible directions, and becoming aware that the earth is in fact a moving vehicle, conceptul problems associated with the Newtonian model would be alleviated.

Another advance organizer would be "forces are applied over time or distance." This particular organizer will subsume the concept of acceleration. Students can perform any kind of activity in which the concepts of impulse (F*t) and work (F*S) are embedded. For example, jumping, throwing, coming to a stop by use of an elastic or rope, and twirling an object tied to a piece of string are good experiences that will form a "roof" under which new concepts and experiences will be subsumed.

Certainly the second law is a quantitative definition of force, and does not pose those immense conceptual difficulties as does the first law. However, without a sound grasp of the concept of acceleration, students should not be expected to relate force to acceleration and therefore understand what the second law is all about. And there is also another problem that seems to complicate things further, namely, that the second law does not become manifest in daily experiences though its simple formula F=ma, as much as it does through its consequences, that is the concepts of impulse and work respectively. What all people experience in their daily life is "forces acting over a distance or over a time interval." People squeeze, push, pull, kick, slap and throw objects. And it is through these experiences that teachers should introduce the second law.

But sensorimotor activities can also be used for the provision of schemata. The schema of Force, for example, could be developed through an activity involving two students on skate-boards who are holding an extended piece of rope, and who are pulling the rope; first only one student pulls, then both pull. It is obvious that this activity does provide the Newtonian schema of force, namely, that forces act in pairs, and that these forces act in opposite directions. For regardless of whether only one student or both of them pull, motion will always take place in opposite directions.

It should be recognized that learning episodes in the form of activities involving the child's own body, and which are designed in such a way that they contain unambiguously general ideas, seem to be a potential educational tool in the hands of science teachers. In actual fact, these episodes may well prove to be both an answer and a complement to current theories of learning since all three domains of the brain are involved simultaneously. In addition, they are the only way to introduce students to general and abstract ideas at an age in which propositions among concepts do not make sense at all, and at the same time help them with the unification of semantic and episodic knowledge, which, as the present study showed, can remain separate and quite isolated from each other.

2. Reinterpretation of Student Ideas about Sensorimotor Experiences

Because intuitive schemata are embedded in, and stem from, bodily experiences with motion and forces, and because these schemata have an explanatory power, students should be helped to reinterpret their experiences. For it is true that, although what students experience and feel is real, it is the interpretations of these experiences and feelings that develop, and subsequently reinforce through additional agents, the intuitive schemata. It is therefore imperative that several misinterpretations stemming from daily experiences be corrected at an early age before students move on to a higher level. A good example is the misinterpretation of the reverse thrust which gives rise to the preconception that the direction of the acceleration is opposite to that of the applied force. And yet this preconception can be changed once students are led to accept that there is no force pushing them backwards or forwards, but instead there are only contact forces that must be provided by the objects with which the human body is in contact. Another common misinterpretation is the idea that motion is the result of two competing forces, such as the force one applies to push a box, and the opposing force of friction. It is obvious that the reintepretation of the idea that the "pushing force is greater than the frictional force" should be the first priority of physics instructors when it comes to the introduction of the First Law.

3. Reintroduction of a Concept at Different Grade Levels

It should be emphasized that the progressive development of the concepts of the Newtonian model over a period of six or eight years is much more realistic than their mastery in one year or a couple of semesters. Physics instructors should design activities that could demonstrate the coherence of the laws of motion as students move from the elementary grades throught high school and even university. It is quite certain that if the Laws of motion are introduced in this spiral fashion at all levels, by the time students leave senior-high school they will have a conceptual understanding comparable to that of a physicist.

4. Explicit Teaching of the Newtonian Model

Given that the Newtonian schema of motion is at variance with the intuitive schemata possessed by students, it would be unreasonable to expect students to understand the Newtonian concepts unless these concepts are defined and used in a way that explicitly shows the difference between the Newtonian and the common sense way of looking at phenomena of force and motion. It would be also unrealistic to expect students to "rediscover" the concepts of the Newtonian model if we take into account the fact that even Galileo himself had not completely abandoned the Aristotelian belief that the perfect and perpetual motion was circular. Moreover, the constraints of time imposed upon any curriculum and any instructional model do not allow for such "rediscoveries."

Another reason why the explicit teaching of the Newtonian model is recommended is that it can facilitate access. For as was discussed in the review of the literature, access is affected by the nature of the problem situations considered during the learning process, and therefore, not only the concepts but also the context and the conditions under which those concepts are applicable are of importance. If different contexts as well as the conditions that "trigger" the applicability of a concept are provided to students, access to relevant information is more likely to occur. In such a way students could abandon the perceptual type of thinking and instead use, for example, the notion that rest and uniform straight line motion are fundamentally equivalent whenever the appropriate context and conditions arise.

The power of modeling is not my own idea since the explicit teaching of the particulate model of matter, the modeling of real-life objects as dimensionless particles, the Bohr model for the atom, to mention but a few, has been utilized by science educators with considerable success (Shelley, 1989). In the same fashion, students should be taught explicity the notion of frame of reference (and at the same time become aware that a frame of reference is different from "a point from which we just perceive motion"), the notion that motion in straight line with constant speed does not involve a net force, and, of course, the idea that rest and motion with constant speed in straight line are the same thing. The idea that students should be taught explicitly the rules and techniques of modeling in general is remarked upon by Hestenes (1992), while Reif and Larkin (1991) have recommended the explicit teaching of scientific knowledge--its goals and structure.

5. Use of Concept Mapping

Taking into account the idea that our concepts in memory are not held as separate or scattered units but are highly organized into schematic sctructures (Anderson, 1985), then a conscious effort on the part of physics instructors should be to develop and promote knowledge structure. Concept mapping of the concepts of the Newtonian model at every level of instruction would very much help towards this development and promotion. There is evidence that concept mapping can promote knowledge structure and hence enhance understanding (Heinze-Fry & Novak, 1990; Novak & Gowin, 1984). Also a recent study by Willerman and McHarg (1991) found evidence that concept mapping at the beginning of instruction resulted in better understanding.

6. Careful Selection of Problem Tasks

No doubt the selection of the problems that will be worked out under both guided and independent practice plays an important role. Yet that selection should be carefully done so that students become aware that a contradiction exists. This awareness of a contadiction, however, goes well beyond the Piagetian idea of disequilibration, since the latter implies a confusion between existing conceptions and new knowledge, while the former is an awareness of the contradictions of one's own thoughts. For this reason, problems should be selected in such a way that the thinking strategy employed in one of the problems contradicts the thinking strategy employed in another.

It is therefore crucial that a general problem situation is selected, and then specific contexts are devised, all of which address the same concept. However, these specific contexts do not imply just a multiplicity of contexts, but rather contexts that closely resemble one another. For only then will students become aware of their "implicit" or "tacit" reasoning strategies. And the advantage ensuing from this awareness will certainly result in a conceptual change as the interviews conducted during the present study showed.

7. Reconsidering the Traditional Approach to Teaching Newtonian Mechanics

The recommendation that the development and subsequent reinforcement of the Newtonian model of motion start at an early age through sensorimotor activities necessitates a reconsideration of our ideas about instructional design. So far students have been taught by starting from straight line motion, supposedly because it "looks" simpler, and then move on to circular motion. Or starting from bodies at rest and then move on to the study of bodies in motion, and teach first about acceleration and then move on to the concepts of impulse and work. "This procedure," as Ausubel et al.

(1978) remind us, "is effective with infrahumans and rote learning of nonsense materials" and not "for meaningful learning" (p. 362). And the problems that continue to plague the teaching-learning process also tell us that this approach does not work.

Perhaps it is time we started from circular motion and the action of forces; that is what is real and what students are aware of, not only during the lesson, but also when they are out of school. And after they get a grasp that "circular motion involves the action of forces" teachers can confidently introduce them to the first law.

Although teaching strategies such as computer simulations through games where an object on the screen obeys the Newtonian laws of motion is a motivating way to introduce students to the Newtonian model, the effectiveness of such an approach for developing acceptable conceptions could be called into question. For understanding is contextual, and therefore students will be able to apply successfully the laws of motion while playing the Newtonian games, and yet retain the intuitive schema resulting from sensorimotor experiences. On the contrary, the provision of sensorimotor activities into which ideas that can subsume less inclusive concepts are embedded seems more promising. In actual fact, this may be the best approach, and, at the same time, a compromise to teach something that goes contrary to common experience through common experience.

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APPENDIX A

INFORMED CONSENT FORM

The purpose of this study is to assess how university physics students understand concepts of Newtonian mechanics, that is, those of force and motion. The study is qualitative, and therefore no mathematical formulae are involved. There are no right or wrong answers; instead, any ideas and beliefs that you may have in your mind, both from instruction and personal experiences with the world, are important.

Your participation in the study will involve an interview approximately one hour in length. Your participation is voluntary, there are no risks or discomforts involved, and you may terminate it at any time during the study. It is hoped that you will benefit from your participation, in the sense that you will acquire a better grasp of the concepts of force and motion. This study can be also seen as a complement to, and extension of, the physics course you are taking from Dr. Peter Hoekse and Dr. Roy Unruh.

Dr. Susann Doody (273-2719, EDC 159) can provide you with additional information regarding the purpose of the study. You are also encouraged to ask further questions about the study after its completion.

If you have questions concerning your rights as a participant of a research project you may wish to call the office of the Human Subjects Coordinator, University of Northern Iowa, (319-273-2748).

I am fully aware of the nature and extent of my participation in this study as stated above, and the possible risks arising from it. I hereby agree to participate in this study. I ackowledge that I have received a copy of this consent statement.

____

Signature of Participant | Date

____

Printed name of Participant | Date

____

Signature of Investigator | Date

APPENDIX B

APPROVAL SHEET

The University of Northern Iowa

October 15, 1993

Yannis Hadzigeorgiou
Curriculum & Instruction, SEC 618
University of Northern Iowa
Cedar Falls, IA 50614

Dear Yannis Hadzigeorgiou:

Your project, "Conceptual Representation of the Newtonian Model of Motion in University Physics Students", which you submitted for human subjects review on October 10, 1993 has been determined to be exempt from further review under the guidelines stated in the UNI Human Subjects Handbook. You may commence participation of human research subjects in your project.

Your project need not be submitted for continuing review unless you alter it in a way that increases the risk to the participants. If you make any such changes in your project, you should notify the Graduate College Office.

If you decide to seek federal funds for this project, it would be wise not to claim exemption from human subjects review on your application. Should the agency to which you submit the application decide that your project is not exempt from review, you might not be able to submit the project for review by the UNI Institutional Review Board within the federal agency's time limit (30 days after application). As a precaution against applicants' being caught in such a time bind, the Board will review any projects for which federal funds are sought. If you do seek federal funds for this project, please submit the project for human subjects review no later than the time you submit your funding application.

If you have any further questions about the Human Subjects Review System, please contact me. Best wishes for your project.

Sincerely,

Norris M. Durham, Ph.D.
Chair, Institutional Review Board

cc: Dr. David A. Walker, Associate Dean
Dr. Susann Doody

APPENDIX C

INTERVIEW SCRIPT

Dear student (by name), first of all I would like to thank you for participating in this study. It is a study that involves philosophy, psychology, and physics, and I am doing it for my doctoral dissertation. I am interested in finding out about how people think about various familiar situations. There are no right or wrong answers. Nor are there any mathematical formulae involved. Therefore I would appreciate it if you gave me whatever ideas you have in your mind. It would be also very useful if you thought aloud by explaining the way, that is "how", you are thinking.

I will first start by asking you some general questions about how objects move and then I will present you with some specific problems. I am hoping that we will be through in about an hour. We might, however, take five or ten minutes longer. If, at any moment, you feel tired or have any problems, please let me know. Stretch out, relax and think.

QUESTIONS FOR ASSESSING PRIOR PROPOSITIONAL KNOWLEDGE

1. How would you define motion?

2. How can you say whether or not a body is moving? If, for example, we are sitting next to each other on an airplane, and we are looking out through the window and see an airplane, would you agree with me that the airplane is not moving, since to me the airplane appears to be at rest?

3. In the case of two people, one aboard a moving a train, and the other on the platform, who watch the same event taking place inside the train, that is the flipping of a coin, what can you say about the path, the time of flight, and the velocity of the coin?

4. In the case of a person standing still in the rain, the rain drops appear to fall vertically, while to a person running in the rain the drops appear to fall at an angle. Who is right? What is the real direction of motion of the rain drops?

5. Can a body move in the absence of forces? Can you give some examples?

6. A spaceship is at rest at a space-station, away from any planetary forces. Suddenly its engine is fired once. What do you think will happen? (Further explanation: How far will the spaceship travel?)

7. Suppose you are inside a vehicle or room which have no windows that allow you to look outside. How can you tell whether or not you are moving?

This is fine. I will now present you with specific problem tasks. I have categorized my problems into three categories. Each category is about one or two general problem situations.

CATEGORY 1 - MOTION OF BODIES IN MOVING FRAMES OF REFERENCE

This category is concerned with two problem situations. The first one, as you can see here in the drawing, is about two friends standing on either end of the roof of a car compartment of a train, facing each other, and who throw the ball they are holding in their hands to each other. The effect of wind or air resistance is considered negligible.

Task 1: Suppose that the train is at rest. What do you think will happen? (Further explanation: will the two friends catch the ball simultaneously?) What is you frame of reference? (Clarification: relative to what point do you perceive motion?) What makes the balls travel the length of the compartment? Suppose now that the train is moving with constant speed in straight line, and suddenly the two friends are throwing the balls. What do you think will happen now? What is you frame of reference? What now makes the balls travel the length of the compartment?

Task 2: Now as you see in this drawing, the two friends are doing the same activity, but this time inside the train. What do think will happen now? What is your frame of reference? What makes the ball travel the length of the compartment?

Task 3: What do think would happen if the two friends rolled the balls, as you can see it in the drawing, towards each other?

Task 4: Now we come to the second problem situation. There is a person, as you can see it in the drawing, sitting in the car compartment of a train traveling with constant speed in straight line. Suddenly the person throws the softball he/she is holding a small way straight up in the air. Where will the softball land? What is your frame of reference? What path does the softball take? What makes the ball travel along that path?

Task 5: Where will the ball land if the person is standing on the roof of the same train? What is your frame of reference this time? What is the path of the ball? What makes the ball travel along that path?

Task 6: Now look at this drawing. What you see is a person running with constant speed in straight line. Suddenly the person throws a baseball straight up in the air. (Clarification: the person applies a vertical force by moving his hand vertically relative to his/her body.) Where will the baseball land?

CATEGORY 2 - MOTION OF BODIES ON THE INERTIAL FRAME OF REFERENCE OF THE EARTH

We now come to the second category. This category is concerned with three general problem situations. The first situation is about an object (like a rock, rocket, or air-balloon) that is thrown or projected straigth up from the ground. I would like you to think about where that object will land. The second situation is about an iron ball that is dropped from a height to the ground. Again, I would like you to think about where the iron ball will land. The third situation is about two airplanes and two boats that are going around the earth.

Task 7: So I start with this drawing that shows a person standing in a yard and throwing a rock straight up in the air. The air resistance is not taken into account. Where will it land? What is your frame of reference? What makes the rock travel up and down?

Task 8: What do you think now about a cannon ball fired by a cannon as shown in the drawing? Where will the cannon ball land? The effect of the air is not taken into account. What is your frame of reference? What makes the cannon ball travel up and down? Do you think the place of landing would change if we took into account the motion of the earth? We assume that, for the time it takes for the cannon ball to go up and down, the earth travels with a constant speed in straight line.

Task 9: Where would a rocket land if it were fired vertically from the ground? The rocket travels straight up until all its fuel is used up and then starts falling straight down. Now, as you can see in the drawing, we take into account the motion of the earth. Again the effect of the air resistance is negligible. What is your frame of reference? What path does the rocket follow? What makes the rocket travel along that path?

Task 10: Now we will take the case of an air-balloon rising vertically above the ground. After it goes high up, it stays there for some time, and then comes back down again. Where will it touch down? The are no winds in the atmosphere to disturb the motion of the air-balloon. What is your frame of reference? What path will the balloon take? What makes the balloon travel along that path?

Task 11: Let's now come to the second problem situation about falling iron balls. As you can see in the drawing, an iron ball is dropped from a point high above the ground by an imaginary hand fixed in space. Where will the iron ball land? The only force acting on the ball is its weight. What is your frame of reference? What path will the iron ball take? What makes the iron ball move along that path?

Task 12: Do you see any difference in your thinking if the iron ball were dropped by an imaginary hand that was near the top of very high building? What would be your frame of reference? What path would the iron ball follow? What would make the iron ball move along that path?

Task 13: Now the iron ball is dropped from a very tall building. As you see in the drawing, the man dropping the ball is standing at the top of the building. Where will it land? The only force acting on the ball is its weight. What is your frame of reference? What path does the iron ball follow? What makes the iron ball move along that path?

Task 14: The third and final situation of this category involves two objects going around the earth. As you see in the drawing, two boats are setting sail from the same place on the equator, and they are going to sail around the earth and along the equator. The boats will sail in opposite directions. Will the boats arrive at the place from which they set sail at the same time? What is your frame of reference?

Task 15: How would now think if two airplanes were to take off from the same place on the equator, and fly around the earth parallel to the equator but in opposite directions? Do you see any difference between this and the previous problem with boat? What is your frame of reference? Do you see any differences between the problem with the boat and the airplane going around the earth, and the problem with the two friends on the train? (Effect of wind is negligible.)

I think you have been an excellent participant. You really thought aloud during the problem tasks. If you think you could devote ten or fifteen more minutes I would really appreciate it. You don't have to stay because I have enough information to do my study, and as I said this was supposed to last approximately one hour. But there is an additional point which I would like to clarify further. So if you think that you can stay and "squeeze" your mind for an other ten minutes, that would be fine. If you feel tired or if you have other things to attend to, that is again fine, and

I want to thank you for your time.

CATEGORY 3 - MOTION OF BODIES WITH CONSTANT VELOCITY

This category has different questions about the relationship between motion and net force.

Task 16: Do think that there is a net force acting on a spaceship traveling in outer space with constant velocity?

Task 17: How about a car traveling against a strong wind? The driver, as you see in the drawing, manages to keep the car in a straight line with constant speed. Do you think there is a net force on the car?

Task 18: Here you see three identical airplanes traveling with constant speed in a straight line. Is a net force acting on the planes, and if yes, on which ones? If yes, which net force is greater?

Task 19: There are three different vehicles: a bicycle, a racing car, and a truck. They are all traveling with constant speed in straight line. What can you say about the net force acting on them?

Task 20: In the drawing you see a person pushing a heavy box along the floor with constant speed in straight line. What can you say about the net force acting on the box?

Task 21: In the drawing you see three identical vans. As you see there is a string hanging from the roof of each van. There is also a bob attached to the end of the string. Which case do you think better shows a van moving with constant speed in straight line?