A CASE STUDY OF A NOVICE COLLEGE STUDENT'S
ALTERNATIVE FRAMEWORK AND LEARNING OF FORCE AND MOTION

A Thesis in
Curriculum and Instruction

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

May 2001
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ABSTRACT

A case study design was used to investigate in detail one female freshman college student's alternative conceptions, alternative framework and learning of force and motion during a short small group instruction and subsequent tutoring interviews. The researcher in this study acted as the teacher of the small group and the tutor for the interviews. The student who participated in this study had a very limited physics learning experience: during her prior schooling she had taken only a seventh grade physical science course. Although she could remember some information, her conceptions were mostly based on her daily experiences and expectations.

Analysis of data showed that during interaction with the teacher-researcher the student seemed to be undergoing conceptual development. However, repeated interviews after the short small group instruction provided evidence that after each session she reverted back to her prior conceptions. An analysis of her alternative conceptions revealed that her alternative framework was significantly different from the Newtonian framework and did not include acceleration for explaining force and motion. It was also revealed that her knowledge base was primarily a collection of expectations for each possible situation. Thus, her learning was characterized as adding or changing factual knowledge to her existing structure.

This study suggests that the concept of acceleration plays a central role in learning force and motion in congruence with Newton's laws. Otherwise, a conceptual integration of the concepts of force, motion, and acceleration cannot be achieved and the knowledge base remains fragmented. Implications for further research are also included.
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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr. Vincent N. Lunetta, committee chair and thesis co-advisor, for his guidance, encouragement, and support throughout my study. I also would like to express my sincere gratitude to Dr. Thomas M. Dana, thesis co-advisor, for his understanding, support, assistance, and expert supervision. My committee members, Dr. Peggy Van Meter and Dr. J. Daniel Marshall, helped me solve many problems regarding the conduct of this study through countless discussions. Therefore, I extend my sincere gratitude to them for their friendship, patience, and endurance. I also extend my deep gratitude to Dr. Peter A. Rubba for his continued support since the very first day I became a member of Penn State's science education community.

I am also thankful to the students who participated in this study. Without their time and effort this study could not have been accomplished. Many other individuals offered their help during this study: fellow graduate students, staff of the Graduate School, and the Department of Curriculum and Instruction. I am indebted to them. I also would like to acknowledge the support from Gazi University, Ankara.

Finally, I would like to express my deepest gratitude to my fiancée Ayse, my family, and my friends who always kept me in their thoughts. Their patience, thrust, and support were inspirational.
Chapter 1

INTRODUCTION

No, there are still difficulties, but the outline of the plot is clear and will develop itself more clearly as we proceed.

− M. Rozer to Lord Peter Wimsey in The Nine Tailors by Dorothy L. Sayers (Morrison, 1990, p.237)

This study draws upon the body of literature and traditions of Science Education Research. More specifically, the issues dealt with in this study are embedded in the domain of physics education research. The goal of science education research, in broad terms, is to address problems in teaching and learning of school science through scientific investigations and hence to inform the science education community about the findings in order to help improve the quality of teaching and learning in science classrooms (e.g. Reif, 1986; Van Huevelen, 1991; McDermott, Shaffer, & Somers, 1994). In doing so, Science Education researchers benefit from the findings in various other closely related fields such as Educational Psychology, Cognitive Psychology, and Cognitive Science which are helpful both in designing a research program and conducting it with a sound approach. Figure 1.1 illustrates how this study can be situated among these "auxiliary" fields. In fact, the relationships between these fields of research are mutually beneficial: they both inform one another and utilize each other's research methods and findings/results.
In the field of science education, researchers have been interested in understanding students, teachers, school settings, and subject matter, as well as the interactions between them (see Figure 1.2). As the clues about the nature of each of these research areas and their complex interactions emerge through rigorous scientific studies, our appreciation of the prevailing intricate procedures in teaching and learning science are enhanced.
The focus of this study was a case of one student's alternative framework and learning about force and motion. In formulating the purpose, locating the problem, and designing the study around the research questions, the researcher utilized the literature from Science Education, Educational Psychology, Cognitive Psychology, and Cognitive Science as they relate to students' learning in physics.

This chapter explains the structural cornerstones of the study: the researcher's theoretical framework, the problem, need for the study, purpose of the study, foci (research questions) of the study, and an overview of the study and employed research methodology.
Merriam (1998, p.47) visualizes the relationships between these fundamental elements as interlocking frames, which can be illustrated as shown in Figure 1.3. Each of those elements describes, in increasing detail, how the entire study is formulated starting from the most general to the most specific. Elaborating the scholarly foundations of the researcher's theoretical orientation is left to chapter 2, which also covers literature relevant to the methodology employed in this study.

![Figure 1.3. Forming/organizing a research agenda starting by researcher's general orientation and narrowing down to a small set of objectives/foci.](image)

1.1 Theoretical Framework:
Student alternative frameworks and conceptual learning/change about force and motion

Three main types of factors can be identified in learning: the social, the affective and the cognitive. In this study I chose only to focus on some of the cognitive factors in the
participant’s learning. When the cognitive aspects of student learning becomes the focus of a study, the researchers' main interests generally lie in one or more of the following:

1. **Teaching.** The nature of successful instructional and curricular practices which lead to meaningful learning.

2. **Process of learning.** The nature of interaction of the student during learning with her/his peers and/or teacher, as well as the learning environment and materials including the subject matter.

3. **Individual cognitive differences.** The nature of the student's cognitive traits and his/her state of cognitive development.

4. **Prior knowledge and experience in science learning.** The nature of student’s background knowledge and existing conceptions, whether or not the learner has gone through formal science instruction and its nature, what the student already knows, and how similar or different her/his conceptions about the natural phenomena to that of the scientific community.

The constructivist view "provides a plausible, functional framework for understanding and interpreting experiences of learning and teaching..." (Treagust, Duit, & Fraser, 1996, p.4). Hence, while formulating this research study and at the end drawing conclusions from the analyzed data, as the researcher in this study, I utilized several bodies of literature, all of which are embraced by the constructivist view of teaching and learning.

Figure 1.4 illustrates how this study is formulated (see also Figure 1.3). The hierarchy is represented in the vertical placement so that the upper layers define the researchers' general orientation while the lower layers give more specifics of this study. The whole acts as a machinery through which the researcher investigated the identified problem for this study.
Figure 1.4. Formulation of the research study in terms of the researcher's interests and theoretical orientation.

The data collection and subsequent on-going interpretation and analyses in this study have been influenced by the literature in the following fields as they relate to teaching and learning science: constructivist view of learning, knowledge, and understanding; students' alternative frameworks about the natural phenomena; conceptual change learning; cognitive structure; analogical reasoning; and individual differences in cognition and learning.
1.2 Problem

Science education is one of the main curricular areas covered almost in all school grades. Physics education, as one of the content areas in science education, often presents difficulties to both teachers and students. It is now widely recognized that students come to classrooms with ideas of their own about the physical phenomena. It is also documented in the literature that many of these ideas are immensely different than the scientifically accepted ones. Studies on student preconceptions report that strongly held misconceptions are one of the main difficulties in learning science. It is determined that even after formal instruction students retain their preconceptions. The prevalence of persistency of student misconceptions has lead researchers to investigate the nature of those conceptions and consequences for teaching and learning science.

Understanding human learning mechanisms has long been a concern of researchers in various fields of both psychology and education. Over the past several decades science education researchers have utilized and developed research methodologies and applied them to various contexts in teaching and learning science. Especially in the last two decades, students' prior conceptions, conceptual understanding and change, and learning processes have been examined from different aspects. Methods have included development of conceptual tests and statistical analysis of results before and after a treatment (e.g., classroom teaching); investigation and characterization of beginner and advanced learners; and comparison of skills and qualities of experts to novices.

Early research in science education mainly focused on identifying learning difficulties in terms of the students' common misconceptions of scientific phenomena. By examining knowledge states and thought processes of novices and experts in specific science domains
together with desired learning outcomes, researchers strived to characterize learners' initial and final states and ways and means of making the transition from a designated initial state to a desired final state (Reif, 1995). This approach to research has relied on inference rather than direct observation of the learners throughout a learning process (Roth, 1998).

With the advent of sound qualitative methodologies, researchers began to question progression and changes in learners' knowledge states, cognitive structures, and interactions with the learning environment (e.g. peers, teachers, subject matter, etc.) throughout a period of time with the hope that such studies can serve as a magnifying glass to the particulars of the problem in hand. This required a thorough analysis of in-depth investigations with thick and rich descriptions and extensive interaction of researchers with participants. Recently there has been a growing interest in investigating learners' entire learning processes during a period of instruction and identifying the learning pathways of individual learners (Niedderer, 1997; Petri & Niedderer, 1998).

Hence, the current study contributes to the science education literature in this way and aims to emulate such prior studies in physics education research by investigating one novice college freshman student's existing and emerging ideas about force and motion. In this study I paid special attention to mechanisms of her meaning making, and her progression of learning during a short small group instruction and a series of interviews which I tutored.
1.2.1 Need for the study

The view that students are not *tabula rasa* and come to learning environments with a plethora of ideas of their own that they construct all through their life experiences is widely acknowledged (e.g. Driver, 1981; Wandersee, Mintzes, & Novak, 1994, p. 181-185; Treagust, Duit, & Fraser, 1996); in fact, many believe that this prior knowledge is *the* most important entity that they possess related to their subsequent learning (Ausbubel's *prior knowledge dictum* as cited in Wandersee, *et al.* 1994, p. 194; and Treagust, Duit, & Fraser, 1996, p. 1). As such, science education researchers have been striving to determine the characteristics of science learners' prior knowledge. By early 1990's they have produced a rich literature on students' understandings of scientific conceptions via over 1000 studies most of which belong to the domain of physics (Wandersee, *et al.* 1994, p. 181).

On the other hand, Pines and West (1986) identify the state of research on conceptual learning that investigates in-depth students' conceptual understanding prior to, during, and subsequent to formal science education as a newly emerging field. According to them this new field relies heavily on qualitative work primarily focuses on students' "misconceptions" or "alternative frameworks." This type of research is concerned with situations in which students are attempting to make sense of relatively large bodies of organized public knowledge or using the knowledge that they have internalized to generate explanations of their experiences in the world. Dykstra, Boyle, & Monarch, (1992, pp. 618-619) also emphasize the need for identifying students' alternative frameworks and cognitive structures together with how and why they differ from that of the scientists'. Stavy (1998) calls attention to the need and importance of comprehensive studies on students'
conceptions and reasoning, the sources of conceptual difficulties, and deep analyses of the scientific content.

diSessa & Sherin (1998) emphasize and demonstrate both theoretically and empirically the importance of building a knowledge structure within a knowledge domain in order to be able to function in that domain effectively. They also emphasize considering and probing learning in this broader scheme rather than focusing on atomistic parts. According to them the essence of conceptual learning has 4 parts: 1) how science learners sense (read out) physical phenomena; 2) how they integrate seemingly different perceptions; 3) how they come to know (build a causal net) when and how to extract relevant information from experiences; 4) how they 'see' the invariance between seemingly diverse situations. diSessa (in press) advocates "moving from before/after studies, and studies that use only constructs (like coding categories) distanced from cogent theoretical terms, to the use of process data to test and illustrate theoretical commitments about concepts, or other theoretical elements of mind, in use and in change."

In their extensive review of the literature the Committee on Developments in the Science of Learning (Bransford, Brown, and Cocking, 1999) recommended that basic research programs in cognition, learning, and teaching need to be continued rigorously:

"while these areas have produced a substantial body of research findings, the research remains incomplete. The framework has been constructed from the earlier research; details now need to be provided in order to advance the science of learning by refining the principles." (p. 236)

They also maintain that among many other factors "a scientific understanding of learning includes understanding about learning processes …" (p. 221)

The inadequacies of "standard" research to provide a comprehensive documentation of "what happens" during an actual learning process have recently led the researchers to
explore alternate routes. "Standard research" refers to all types of research which rely on inference rather than direct observation of the process and are not indeed concerned with the process itself. Such studies include various forms of non-experimental designs (e.g., descriptive research, survey research) and experimental designs (e.g., pretest-posttest control group design). As an example, surveys may detect widespread deficiencies, but give limited insights into how learning occurs, or why the intended learning often does not take place. (see and add from Taber, 2000). On the other hand, learning process studies require fewer inferences and capable of revealing unforeseen results. Thus, determining learning trajectories through in-depth continual studies is crucial for the advancement of science education (Roth, 1998).

Correspondingly, Niedderer, Goldberg, and Duit (1992) asserted that

"Little research has been reported that documents student understanding during the learning process. In a constructivist framework of teaching and learning it becomes important to have information about how the ideas of individual students and groups of students emerge during learning. This suggests a shift in research focus from pre-post "snapshots" of understanding to "strobe" pictures of the learning process." (p. 21) [Italics original]

A number of learning process studies have been reported in different domains of physics with different emphases in analysis. The duration of these studies varied from hours to weeks and even extended to months. Table 1.1 gives a non-exhaustive list of single-participant learning process case studies:
Table 1.1. Examples of case studies with unit of analysis of 1 (a non exhaustive list).

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year reported</th>
<th>Domain</th>
<th>Theoretical framework</th>
</tr>
</thead>
<tbody>
<tr>
<td>Séré</td>
<td>1992</td>
<td>Structure of Matter</td>
<td>Learning Process</td>
</tr>
<tr>
<td>Scott</td>
<td>1992</td>
<td>Structure of Matter</td>
<td>Learning Process</td>
</tr>
<tr>
<td>Schwedes &amp; Schmidt</td>
<td>1992</td>
<td>Electric Current</td>
<td>Conceptual Change</td>
</tr>
<tr>
<td>Katu</td>
<td>1992</td>
<td>Basic Electricity</td>
<td>Conceptual Learning/Change</td>
</tr>
<tr>
<td>Niedderer &amp; Goldberg</td>
<td>1994</td>
<td>Electric Circuits</td>
<td>Learning Process</td>
</tr>
<tr>
<td>diSessa &amp; Sherin</td>
<td>1998</td>
<td>Force and Motion</td>
<td>Conceptual Learning/Change</td>
</tr>
<tr>
<td>Maria</td>
<td>1998</td>
<td>Gravity, shape of the earth, day and night, and seasons</td>
<td>Conceptual Learning/Change</td>
</tr>
<tr>
<td>Hynd</td>
<td>1998</td>
<td>Gravity</td>
<td>Conceptual Learning/Change</td>
</tr>
<tr>
<td>Taber</td>
<td>2000</td>
<td>Chemical Bond</td>
<td>Learning Process</td>
</tr>
</tbody>
</table>

In short, the need for this study can be summarized as follows: prior research, which had focused on the nature of students' alternative conceptions and inferences regarding learning (i.e., conceptual change), was primarily based on data collected before and/or after an instructional period. Similarly, how one came to function more efficiently in a specific domain was also studied by focusing on experts and novices. Identifying the states of both novices and experts gave leverage to reason about how one might evolve in her/his learning. In addition, although current literature documents that students' alternative conceptions often persist even after instruction (Wandersee, et. al. 1994, p. 186), little is known about the nature of that persistence. These concerns can only be answered via in-depth long-term studies which will typically focus on individuals.
1.2.2 Purposes of the study

In this research study I am seeking a detailed account of knowledge claims that already exist in the literature (i.e., existence and persistence of students' alternative conceptions, and in broader terms, concept learning and conceptual change). The purpose of this research study is to gain insights about the nature of one student's alternative framework and learning while helping her develop her learning about force and motion. The primary research objective was to explore, describe, and explain the student's learning process in depth. Therefore, existing theories of learning in science were not tested as a result of this study but rather utilized in building the research methodology and subsequently in the interpretation and analysis of the data.

I did not aim to prove or disprove the effectiveness of specific instructional strategies, which would be well beyond the realm of this case study. Rather, the aim of this study was to portray a case of a learning process with possible successes and failures along the way and to evaluate the whole process in its entirety to develop an understanding of how the different parts might contribute to the whole. My intent was to investigate a single case as thoroughly as possible to support any achievable conclusion for the case and to generate hypotheses by direct observational evidence rather than by indirect inference in order to gain insights that might inform teaching and research. Hence, this study can be best characterized as 'descriptive, explanatory, and exploratory' rather than being 'confirmative.'
1.2.3 Research questions

An exploration, description, and explanation to answers of the following questions were sought throughout the period of time that I interacted with the student in a series of formal small group teaching and individual tutoring interview sessions:

1. What is the student's alternative framework about force and motion?
2. How does the student respond to cognitive challenges about force and motion during group teaching and individual tutoring interview sessions?
3. How did the student's learning about force and motion progress during the course of this research study?
   a. What were the nature and extent of her learning after the group teaching, and each individual tutoring interview session in spring semester 1999 and spring semester 2000?
   b. Why were the student's alternative conceptions persistent or subject to change?

1.2.4 Significance of the study

This research study is intended to exemplify how several pieces of knowledge shape one's overall alternative framework about force and motion and, in turn, how this alternative framework influences her subsequent learning while interacting with a teacher-researcher. More explicitly, by employing a comprehensive data gathering methodology, I aimed to illustrate how a novice 'sees' the physical phenomena (i.e., force and motion) different than an expert and makes sense of the scientific explanations regarding those phenomena.
Through the researcher's interpretations and analysis of the student's alternative framework it is expected that promising ideas about the nature of conceptual change phenomenon may be suggested by the study. Obviously, this extensive account of learning can be subjected to further interpretation and analysis by other researchers who are interested in different aspects of conceptual change. The results of this study, therefore, should yield preliminary hypotheses concerning students' alternative frameworks, about force and motion in particular and about scientific phenomena in general. Beyond the present study the results will be helpful for developing a future research program and for planning curricular activities. In the last analysis, this will be useful for both researchers working in the field and physics/science teachers.

1.3 Overview of the study

This research study was designed as a case study with a unit of analysis of one. At the time of the study I was involved in a cooperative effort for designing, developing, and delivering a new project-based introductory physical science course intended primarily for elementary education majors at The Pennsylvania State University. I became familiar with the student profile enrolling in this class during fall semester 1998 and spring semester 1999 prior to starting data collection.

Four students were selected for a case study group teaching based on their good level of communication with me which developed during the first five weeks of the course. Then, I taught these students privately for about 10 weeks from mid-February to late April 1999. At the beginning of this period, concepts of force and motion were covered during the first
three instructional sessions. Afterwards the researcher interviewed all four students several times. June (a pseudonym) became the major participant in this study because of her and long-term availability.

1.4 Overview of the methodology

Until today, research has been pursued along two main lines, directed toward understanding the general or the particular. Sound research methodologies of these two traditions, labeled as quantitative (employs deduction) and qualitative research (employs induction) respectively, have helped us understand educational problems from different perspectives. Merriam (1998, p.6) notes that "qualitative researchers are interested in understanding the meaning people have constructed, that is, how they make sense of their world and the experiences they have in the world… The key concern is understanding the phenomenon of interest from the participants' perspectives, not the researcher's."

In this research study a qualitative case study approach was adopted to delineate one novice college student's alternative conceptions and learning about force and motion. The participant was a female freshman, majoring in elementary education, who was enrolled in an introductory physical science course at the time of the study. Her prior experience in learning physical sciences was limited. To further investigate and analyze her long-term learning, the study was expanded over a fourteen-month period. Reported in this thesis is her journey of learning.

The data gathering methods in this study were: extended response-free recall pre-post tests, interacting with the participants during a videotaped formal class period in which
the researcher acted as the teacher of a small group of students, one-on-one tutoring interviews about instances and events, standardized cognitive and content specific tests, questionnaires and worksheets prepared by the researcher, a word association task, and student artifacts.

My involvement in the study as a teacher was crucial in data gathering since this involvement enabled me to act as an instrument. My immediate, on the spot decisions during the process of data collection substantially shaped this study.

1.5 Definitions of terms

Alternative Conception: Refers to experience-based explanations constructed by a learner to make a range of phenomena and objects intelligible, but also confers intellectual respect on the learner who holds those ideas: it implies that alternative conceptions are contextually valid and rational and can lead to even more fruitful conceptions (e.g. scientific conceptions). (Wandersee, Mintzes, & Novak, 1994, p. 178).

Alternative Framework: The sets of beliefs or expectations science learners hold about the way the natural phenomena occur which might differ from the currently accepted scientific view and from the intended outcome of learning experiences (Driver, 1981). An alternative framework is inferred by researchers based on what they sense what science learners think. Hence, it is a knowledge structure which is deduced from a set of alternative conceptions (Wandersee, Mintzes, & Novak, 1994, p. 178).

Concept: A perceived regularity in events, objects, or other concepts designated by a label (usually a word) (Novak, 1996, p. 32). A concept is a locus of meaning – a sort of
summary of all the prepositional relationships in which that concept participates (Pines & Leith, 1981).

Conceptual change: Learning as a process in which a person changes his or her conceptions by capturing new conceptions, restructuring existing conceptions, or exchanging existing conceptions for new conceptions. In this case, there is only one entity and a different one after. Here change means extinction of the former state. Therefore, change means an exchange of one entity for another (Hewson, 1996, p.132).

Cognitive challenge: Experiments, events, demonstrations, observations, ideas, models, theories, analogies, etc., that can create dissonance with one's current conceptions and help stimulate or bring about conceptual change toward a scientific conception that is new to the learner.

Conceptual development: The process of learning during which science learners make a genuine effort to make sense of the formal, symbolic knowledge presented (as opposed to rote learning numerous, isolated bits of information and memorizing lists of propositions) and as a result to integrate and differentiate the symbolic knowledge within their cognitive structure (Pines & West, 1986, p. 592).

Conceptual exchange: The process of coming to accept a new conceptual framework while abandoning what was previously held to be true, when confronted with a substantial reality clash between scientifically accepted conceptions and one's own alternative framework (Pines & West, 1986, pp. 593-594).

Conceptual resolution: Refers to resolving conflicts between what science learners believe to be true and what they are told is true in favor of the scientifically accepted
conceptions, when they have alternative conceptions that somewhat clash with the scientifically accepted ones (Pines & West, 1986, p. 593).

**Declarative knowledge.** Cognizance or awareness of some object, event, or idea; also described as *knowing that*. When a person *knows that*, she or he is able to define or describe the objects of that knowing but is not necessarily able to use that knowledge since declarative knowledge does not imply understanding (Jonassen, Beissner, & Yacci, 1993, p. 3).

**Dissonance.** A sensed discrepancy between a conception and another entity, observation, or other conception (also called dissatisfaction, unease, dis-equilibrium). *Strong dissonance* refers to an explicit, strong incompatibility between a preconception and a new conception ('conflict' has been thought of as the strongest form of dissonance), whereas *weak dissonance* refers to a mild sensed discrepancy (Rea-Ramirez, 1998).

**Learning.** The ability to memorize knowledge (facts and procedures) and subsequently retrieve and apply relevant aspects of this knowledge in order to make sense of newly emerging circumstances.

**Meaningful learning.** Substantial nonarbitrary incorporation of a learning task into relevant portions of cognitive structure, so that a meaningful relationship is established; it implies that the learning material becomes an organic part of a particular, hierarchically organized conceptual system. It becomes imbedded within the latter system in a *relational* sense, that is, independently both of the verbatim integrity of the material and of specific, arbitrary connections within the material (Ausubel, 1963, p. 42).

**Procedural knowledge.** Describes how learners use or apply their declarative knowledge: *knowing how*. Procedural knowledge entails the interrelating of schemas into patterns that
represent mental performance which are in turn represented mentally as performance schemata. Procedural knowledge is dependent on complex interconnections between ideas. Solving problems, forming plans, and making arguments are examples of activities that entail procedural knowledge. In performing these activities, learners must access and interrelate relevant schemata and extract the relevant attributes to apply to the situation (Jonassen, Beissner, & Yacci, 1993, p. 3).

*Rote learning.* Learning by incorporating tasks into cognitive structure in the form of arbitrary, intramaterial associations, that is, as discrete, self-contained entities organizationally isolated, for all practical purposes, from the learner's established conceptual system (Ausubel, 1963, p. 43).

*Structural knowledge.* Refers to how information within a knowledge domain is organized. Mediates the translation of declarative into procedural knowledge and facilitates the application of procedural knowledge. It is the knowledge of how concepts within a domain are interrelated. It is not enough to *know that.* In order to *know how,* one must *know why.* Structural knowledge provides the conceptual basis for *why,* it describes how the declarative knowledge is interconnected. Structural knowledge is also referred to as cognitive structure, or as conceptual knowledge (Jonassen, Beissner, & Yacci, 1993, p. 4).
Chapter 2

LITERATURE REVIEW

There is reason that all things are as they are, and did you see with my eyes and know with my knowledge, you would perhaps better understand.

–Count Dracula in Dracula by Bram Stoker (p.23)

2.1 Introduction

There exists a dissatisfaction with current teaching practices in science education. von Glasersfeld (1992, p. 34) states that although it may seem that students are developing an understanding when they act and respond in certain required ways, this, in fact, might not be the case if they are just repeating what the teacher or the textbook says, since it does not indicate a conceptual fit. Woods & Thorley (1993) also vividly express similar experiences and concerns:

In analyzing case-study evidence for students' understanding before and during instruction and finally about two months later, it has become clear to us how enormously difficult it is to help a student achieve a deep and robust understanding. Lessons which had seemed powerful and successful at the time appeared rather less so when the later interviews revealed that students had reverted to earlier naïve conceptions, could remember the 'right answer' but not justify it, or, in some cases, had seriously misconstrued key aspects of a lesson. (p. 25)

As these remarks demonstrate, documenting students' learning as success or failure via single snapshot probes has certain drawbacks. It is not known and cannot be known how
or why students respond in certain ways if only before and after 'pictures' of their learning are obtained. Indeed, in defining the 'after' status of one's knowledge for the purposes of describing and explaining learning that takes place due to an instructional intervention, it is assumed that learning is either a linear gradual transition from one state to another (desired) or, just like a digital system, can be probed as the binary logic requires as 1 (took place) or 0 (did not take place). Such a point of view does not account for any fluctuations in the conditions and/or status of learning during the process.

On the other hand, if learning is presumed to be a 'process' that requires the learner's active involvement and is affected by the nature of the learners' prior knowledge then stroboscopic probes become necessary. Only in this way can direct evidence about the nature of learning be obtained if one wishes to avoid indirect inference. Along this line of thinking White and Gunstone (1992) emphasize another aspect of the subjective nature of understanding and any probing of it. They assert that:

understanding of a concept or of a discipline is a continuous function of the person's knowledge, is not a dichotomy and is not linear in extent. To say whether someone understands is a subjective judgment which varies with the judge and with the status of the person who is being judged. Knowledge varies in its relevance to understanding, but this relevance is also a subjective judgment (p. 7).

### 2.2 Theoretical framework of the study

The two purposes of this study, namely revealing a student's alternative framework and tracking her learning throughout a period of time, rest on a body of literature that has emerged within the last several decades. The primary fields of research that contribute to this study are: 1) the constructivist view of science education and science education research
2) students' alternative conceptions and frameworks of the natural phenomena, 3) conceptual change learning, and 4) learning as building a cognitive structure/knowledge organization. These four fields define the boundaries of the theoretical framework of this study which are delineated in the following sections.

Let me begin with facts—bare, meager facts, verified by books and figures, and of which there can be no doubt. I must not confuse them with experiences which will have to rest on my own observation or my memory of them.

—Jonathan Harker in *Dracula* by Bram Stoker (p. 33)

### 2.2.1 Constructivist approach to teaching and learning of science

Constructivism is a theory of learning (knowing) and knowledge; it is an epistemological stance. Constructivists oppose the view of teaching that is equated with a mere transmission of information to students since it quite often implies learning by memorization (Gallagher, 1993, p. 181; Dana & Davis, 1993, p. 326). Rather, constructivists assume that knowledge cannot merely be transferred to a passive receiver from another individual; it must be constructed by each individual (von Glasersfeld, 1993, p. 26; Roth, 1993, p. 146). According to this view individuals actively construct knowledge through their life experiences in their physical and/or social environment. Thus, school settings can be perceived as knowledge "construction sites" if opportunities for students' active engagement in learning are created, whether they are individual, through interaction with the teacher or peers (Roth, 1993, p. 149).
Constructivism, inevitably, also has to deal with the ontological question of what truth entails. von Glasersfeld (1993, p. 25-27), who has been the main driving force behind constructivism in education, replaces the notion of truth with "viability" and thus confines it exclusively to the experiential field. Although constructivism accepts the idea of the existence of a "real world," it denies the possibility of getting to know that reality with any certainty. In this way, constructivists envision knowledge and knower as inseparable, making the nature of the relationship between the two rather subjective (Treagust, et al., 1996, p. 5-7). Therefore, constructivism calls for a distancing from the objectivist/positivist position that a true knowledge exists outside the learner (Dana & Davis, pp. 325-326).

Hence, constructivists attribute a critical importance to learners' prior knowledge and process of learning during which the construction of knowledge takes place. In any event, construction of knowledge takes place independent of the nature of instruction. Teaching, from the constructivist perspective, is characterized as aiming explicitly "to help students make the constructions that lead to understanding of the scientific point of view" rather than providing information through a teacher or a textbook (Treagust, et al., p. 5-8).

Since learners, according to the constructivist view, are not empty vessels that simply get filled with knowledge during instruction (Roschelle, 1998), what they already know is regarded as a major determinant of their subsequent journey during learning. Over the years, researchers have investigated what students already know about why and how things happen in nature and how that knowledge affects their learning during science instruction. Because of this emphasis on learners' prior knowledge, a tremendous number of research studies have been conducted to find out characteristics of naïve conceptions about the natural phenomena. In the next section I will detail research on students' ideas about force and
motion. Results of relevant studies will be outlined and cultivated in order to shed some light onto the rest of this study.

2.2.2 Students' alternative conceptions about force and motion

Aiello-Nicosia & Sperandeo-Mineo (2000) cite documented evidence for a growing dissatisfaction with the quality of physics teaching and learning, as well as and there are calls for widespread changes in objectives and in the practice of teachers and learners. As an example Van Huevelen (1991, p. 891) points out that:

Students enter introductory physics courses with strongly held preconceptions that are often misconceptions. They use primitive formula-centered problem-solving strategies. Their knowledge consists of a small number of facts and equations stored randomly in the mind. Many studies indicate that students leave our courses in about the same status as they entered. They have the same preconceptions and misconceptions as when they started. They still use formula-centered problem solving methods. They see physics problems as springs, inclined planes, ropes and pulleys, whereas experienced physicists see the problems in terms of basic physics concepts.

Since Ausubel (1963, 1968), science education researchers have increasingly realized the importance of the knowledge that individuals bring to learning situations (McDermot, 1991; Wandersee, Mintzes & Novak, 1994; Dekkers & Thijs, 1998). The nature of students' preconceptions and the task of leading students from their initial states to final desired states through instruction have challenged science educators (Reif, 1986).

Duit (1993) states that "there is no doubt that the constructivist view has been a most powerful and fruitful driving force in research on students' (and teachers') conceptions, i.e., on research that seriously takes the conceptions of all the actors in instructional settings, such as science instruction in school, into consideration." By 1993 over 300 studies had been
conducted on students' conceptions in mechanics including the topics of force and motion; work, power, energy; acceleration; gravity; pressure; density; floating; and sinking (Duit, 1993). Many difficulties in learning physics are now thought to stem from students' beliefs and expectations about the physical phenomena which are in odds with the scientifically accepted ones.

2.2.2.1 Literature base on students' alternative conceptions of force and motion

Through the years learners' alternative conceptions about force and motion have been identified. A number of selected research studies in the domain of force and motion are outlined below.

Clement (1982) reported on the nature of the 'motion implies force' conception. He noted that Newton's second law \( F=ma \) contradicts the students' intuitive ideas because in real world situations friction always exists. Therefore, one must keep pushing in order to maintain a constant state of motion. Clement commented that this preconception is not automatically replaced by the scientific conception simply because students take a physics course. He added that during instruction "Newtonian ideas are simply misinterpreted or distorted by students so as to fit their existing preconceptions; or they may be memorized separately as formulas with little or no connection to fundamental qualitative concepts" (p. 70).

Halloun and Hestenes (1985a) created a diagnostic instrument to evaluate students' knowledge states in mechanics. They probed 22 students' conceptions through this diagnostic instrument and by means of interviews. The results helped form a taxonomy of
"students' common sense concepts about motion" (Halloun and Hestenes, 1985b). They reported that students' conceptions were similar to the ideas of Aristotle (Aristotelian physics) and Buridan (Impetus physics). The results showed that establishing a linear relationship between magnitude of force on an object and its speed was common among the students. They also tended to hold the conception that acceleration is due to increasing force. The study also showed that the students possessed a variety of ideas about gravity which were not associated with the Newtonian framework of motion. Students did not necessarily view gravity as a force; instead, the conception of 'heavier objects fall faster' was common among them.

McClosky, Caramazza and Green (1980) investigated 47 undergraduate university students' understandings of force and motion. Among these students 15 had never taken a high school or college physics course, 22 had completed one high school physics course, and 10 had completed at least one college physics course. The results revealed that many students, including those who had taken a physics course, held the conception that "when an object is passed through a curved tube, it will continue in curved motion even when no external forces act on it." Even more surprisingly, some students expressed their ideas that the more dramatic the curvature of the tube (or perhaps the longer the object is in the curved tube), the more curved its motion will be after it emerges. Kaiser, Jonides, and Alexander (1986) found that for similar problems, if it was presented in a familiar form rather than in abstract form, the subjects responded correctly more often. Researchers also studied (McClosky, 1983; and McClosky, Wasburn, & Felch, 1983) subjects' predictions of trajectories of objects given an initial speed. He found that many people failed to predict correctly how objects would behave in such a situation.
Watts and Zylbersztajn (1981) investigated 125 14 year-olds. They found that a great majority of the students associated force with motion: if a body is moving there is a net force acting upon it in the direction of movement. If a body is not moving there is no force acting on it.

Gómez (1993) reported that among 110 college students (72 female, 38 male), who were enrolled in an introductory physics course, 91.9 % initially believed that motion implied force. After taking the course, 87.3 % still retained their original conceptions. Even more interesting is that prior to the course 34.9 % of the students believed that a constant force produces a constant speed, but after taking the course the number actually increased to 50.9 % of all students. In plain words, rather than helping the students learn force and motion according to Newton's laws, taking the course had an adverse affect on students' understanding of physical principles.

Sadanand and Kess (1990) studied 57 college-bound high school senior students. They inferred three common student misconceptions: i) Animate objects must exert a force to hold things up, but inanimate objects do not have to do so; ii) A constant force is necessary to maintain a constant motion; iii) Reaction forces are less "real" than action forces. Osborn (1985, p.46) used the interviews about instances technique with 40 students and illustrated that the intuitive adherence to impetus physics as opposed to the Newtonian view of force and motion among students' of ages between 13 and 17 is common.

Minstrell (1982) and Terry, Jones, and Hurford (1985) studied students' explanations of bodies at rest. They found that when an object sitting on a table is considered, a significant percentage of students' were ignoring the normal force on the object due to the table. Students even considered that it was the air pressure keeping the object in place.
Watts (1982) interviewed 20 secondary school students of ages 12-17. Those interviews revealed several misconceptions regarding gravity: i) Gravity is a force that requires a medium to act through; ii) where there is no air, there is no gravity; iii) gravity increases with height; iv) gravity is constant – moving objects try, and fail, to 'counteract' gravity; v) gravity begins to operate when objects start to fall down and continues until they are at rest on the ground; vi) gravity is a large force; vii) gravity is selective – it does not act on all things in the same way, nor on the same things in the same way at all times; viii) gravity is not weight.

In another study Watts (1983) employed the *interviews-about-instances* technique and investigated 12 students' alternative frameworks. The students' ages ranged between 11-17. He defined an alternative framework as "a person's imaginative efforts to describe and explain their physical world," and identified 8 frameworks among these students (see Table 2.1).
Table 2.1. Students' frameworks of force identified by Watts (1983).

<table>
<thead>
<tr>
<th>Alternative Framework</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affective Forces</td>
<td>Forces are obligations to complete an action against some resistance.</td>
</tr>
<tr>
<td>Configuration Forces</td>
<td>Objects restrained in a position have force.</td>
</tr>
<tr>
<td>Designated Forces</td>
<td>Forces are designated to those objects that are causing or will cause events to occur.</td>
</tr>
<tr>
<td>Encounter Forces</td>
<td>When two or more forces come together they can be combined to change the movement of an object.</td>
</tr>
<tr>
<td>Impact Forces</td>
<td>Moving objects are a force, which is made manifest when the objects collide with some other body.</td>
</tr>
<tr>
<td>Motive Forces</td>
<td>If a body is moving there is a force acting upon it in the direction of movement. If body is not moving there is no force acting upon it.</td>
</tr>
<tr>
<td>Operative Forces</td>
<td>Force is an action. The amount of force is proportional to the amount of activity taking place.</td>
</tr>
<tr>
<td>Substantial Forces</td>
<td>Forces are positive actions that are effective when they come into contact with objects.</td>
</tr>
</tbody>
</table>

Many studies revealed that students did not consider gravity a force (push or pull). In a large sample survey Bar, Zinn, and Goldmuntz (1994) found that more than 50% of children age 7-13 held the conception that a heavier object would fall first if released from the same height with a lighter object.

The existing body of literature in physics education research has accumulated evidence on students' understanding of force and motion. Driver, Squires, Rushworth, and Wood-Robinson, (1994, p. 149) summarized the students' main ideas about force and motion from the research studies as follows:

- if there is motion, there is a force acting;
- if there is no motion, then there is no force acting,
- there cannot be a force without motion,
- when an object is moving, there is a force in the direction of its motion;
a moving object stops when its force is used up;

- a moving object has a force within it which keeps it going;

- motion is proportional to the force acting;

- a constant speed results from a constant force.

Gilbert and Zylbersztajn (1985) evaluated the research findings about students' alternative frameworks and asserted that the motion implies force conception originates from the novices' consideration of friction in a totally different framework than the Newtonian. In their opinion this points to an ontological problem, since inertial view of motion attributes the same ontological status to both uniform motion and rest situations which is anti-intuitive for the students.

2.2.2.2 Students' conceptions of acceleration

Orton (1984), Onslow (1988), Thompson & Thompson (1994), Thompson (1994), and Confrey & Smith (1994) studied students' understanding of the concept of rate and concluded that it should not be taken for granted that students develop this concept trivially and inherently. Rather they experience difficulties in conceptualizing the concepts of 'rate' and 'rate of change,' in part because both acceleration and velocity involve rates of change.

Jagger (1987) investigated 13 freshman university students' understanding of the concept of acceleration. These students were majoring in mathematics, and the study yielded several results regarding their conceptions. She concluded that one difficulty stemmed from commonly handling velocity and acceleration in situations where they are parallel to each other in the same or opposite directions. This, occasionally causes students to omit other
cases where velocity and acceleration make an angle with respect to each other. Defining acceleration merely as 'rate of change' helps little in teaching the concept if its vectorial characteristics are skipped. When conceptualization is based on experiences, the word acceleration implies an increase in speed, and, in real life situations, it is not easy to feel change in speed if it does not occur rapidly.

Jones (1983) used interviews-about-events and interviews-about-instances techniques to investigate students' understanding of speed, velocity, and acceleration. Her sample consisted of 30 students of ages 11-16 from 5 different grades levels and 5 different schools. She found a common theme in the students' explanations of speed: students associated speed with "catching up" and the respective positions of two different objects. The conception was that if two objects were moving and one was approaching the other from behind then it ought to move faster, but during the split second that they align together they have the same speed. Data showed that the percentages of students adhering to this conception were decreased with increasing grade level. For velocity, students held a variety of ideas and only one student associated velocity with speed and direction of motion. In this study, a great majority (60 % and up) of the students across all grades held the conception that increasing speed implied increasing acceleration.

Trowbridge and McDermott (1980) investigated college students' qualitative understanding of acceleration by means of interviews. They used two tasks: i) Piagetian acceleration task, and ii) 'Acceleration Comparison Task' that they developed to assess qualitative understanding of the ratio of $\Delta v/\Delta t$. They found that even a basic application of the definition of acceleration to relevant situations posed major and persistent difficulties for many students:
Although most students could define acceleration in an apparently acceptable manner after instruction, they could not use this definition to determine a procedure for comparing the accelerations of two moving objects (p. 251).

2.2.3 Conceptual change

The notion of conceptual change, within the confines of the constructivist point of view, has helped scholars develop a rich literature about students' learning in science. Scholars observed that:

i) students come to science classrooms with conceptions of their own about natural phenomena which are often non-scientific but self-consistent;

ii) such student generated conceptions, although varied, have commonalities over all age groups and even historical roots;

iii) such alternative conceptions cannot simply be over-written with scientifically accurate ones during science instruction since they tend to form a meaningful whole and a way of 'seeing' the world for the students, and are persistent in nature.

These observations have led them to conceive of learning as a change from one (set of) conception(s) to another, which is congruent with scientific theories and intended teaching/learning outcomes.

In 1982 Posner, Strike, Hewson, and Gertzog introduced a theory of conceptual change in order to explain "the substantive dimensions of the process by which people's central, organizing concepts change from one set to another set, incompatible with the first"
They regarded learning as a "rational activity" and put forth the conditions for accommodation of new conception(s) as follows:

1. There must be dissatisfaction with existing conceptions
2. A new conception must be intelligible
3. A new conception must appear initially plausible
4. A new concept should suggest the possibility of a fruitful research program.

Posner, et al. (1982) propose that an individual's current concepts form a conceptual ecology. Together with the level of meeting the above mentioned conditions for accommodation of a new concept, features of an individual's conceptual ecology determine the direction of accommodation. Posner, et al. cited five features through which a conceptual ecology can be characterized: i) the nature of anomalies in the existing conceptions; ii) related analogies and metaphors; iii) individual's epistemological commitments; iv) metaphysical beliefs and commitments; and v) knowledge in other fields and about competing concepts.

Smith, diSessa, and Roschelle (1993) challenge the notion of replacement of one conception with another during the conceptual learning process. They assert that such a characterization of conceptual learning is contrary to the constructivist point of view since it claims a discontinuity during learning. If conceptual change implies a discrete leap in one's knowledge, it cannot be a basis for meaningful learning. Smith, et al. propose a constructivist learning theory according to which students' prior conceptions serve as resources for cognitive growth within a complex systems view of knowledge. This theory aims to illustrate the interrelationships between different knowledge elements within a learner's framework and highlights learning as refinement and reorganization. Smith, et al. propose that research
should now focus on the evolution of individuals' long-term learning by identifying both knowledge organizations and their generality, rather than focusing on the (flawed) nature of conceptions. Dykstra, Boyle and Monarch (1992) also emphasize the importance of probing how students' organize knowledge before and during learning. They indicate that conceptual learning can be attained by targeting a change in the organization of knowledge if students' knowledge structures can be probed and compared to the scientifically accepted one.

2.2.4 Knowledge organization/cognitive structure

A person's development of understanding is characterized by acquisition and linkage of new elements into the existing pattern of associations between elements of knowledge (White & Gunstone, 1992, p. 142). Sutton (1980) attributes a critical importance to learners' prior knowledge, but he states it is also a concern to understand how various ideas are interconnected in the learner's mind and how s/he sees the world. Probing a learner's "structure of ideas" can be achieved in several ways:

- Clinical tutoring interviews,
- Word association or word sorting tasks,
- Exercises in writing definitions or to choosing a preferred statement from several correct ones, and
- Tasks which involve bipolar dimensions on which an idea is rated (p.109).

Shavelson (1974, p. 231) cites six reasons to emphasize the importance of structural knowledge:

1. It is required for a full understanding of the subject matter,
2. It enhances the retention of subject matter,
3. It facilitates problem solving,
4. It leads directly to transfer to similar and (perhaps) new situations,
5. It results in intellectual excitement,
6. It leads to an aptitude for learning.

Shavelson (1972) investigated the correspondence between content structure and cognitive structure by means of achievement and word association tests. By comparison of treatment \((N=28)\) and control \((N=12)\) groups he found that with instruction achievement increased significantly cognitive structure changed considerably, key concepts became more interrelated, and cognitive structure corresponded more closely to content structure.

2.3 Qualitative inquiry and methods of case studies in science education research

A case can be a person, an event, a program, an organization, a time period, a critical incident, or a community. Regardless of the unit of analysis, a qualitative case study seeks to describe that unit in depth and in detail, in context and historically (Patton, 1990, p. 54). Case studies are distinguished from other qualitative studies by their intensive descriptions and analyses of a single unit or a bounded system. "A case study design is employed to gain an in-depth understanding of the situation and meaning of those involved. The interest is in process rather than outcomes, in context rather than a specific variable, in discovery rather than confirmation" (Merriam, 1998, p. 19). Similarly, Rossman and Rallis (1998, p. 70) also emphasize the particularistic focus of case studies. They characterize case studies as descriptive, holistic, heuristic, and inductive, and they assert that a researcher may seek to
understand a larger phenomenon through close examination of a specific case and therefore focus on the particular.

Case studies are indeed very popular among qualitative researchers because they have been used successfully to gain beneficial insights regarding many issues. Case study approach is also familiar in the fields of education, medicine, law, psychology, and sociology. Another reason researchers view this as a preferred tradition is because of the vast array of methods used to collect information (interviews, observations, documents, audio-visual materials, archival records, etc.). These multiple sources of information can provide researchers with a vast amount of information that would better enable them to present an in-depth picture of their cases.

Although the case study is popular among qualitative researchers, it also poses many challenges as well. The first challenge is to identify the case and to decide what boundaries to set. Another concern regarding a case study approach to qualitative research is securing enough information needed to present an in-depth picture of the case. According to Stake (1994, p. 238), case study research faces a strategic choice in deciding how much and how long the complexities of the case should be studied.

2.3.1 Constructivist Teaching Experiment Methodology

The Constructivist Teaching Experiment (C-TE) methodology focuses on i) advancement of learners’ construction of their subject matter knowledge, and ii) improvement of teacher-researcher’s explanations regarding the underlying processes involved in this learning (Tzur, 1994). According to Cobb and Steffe (1983), each student’s
experience is unique in any situation, therefore rather than teacher’s interventions during instruction, it is student’s interpretations of those interventions which leads to construction of knowledge. Thus, nature and content of any knowledge construction is determined by the learner. Consequently, the teacher-researcher’s task is not to study the student’s acquisition of preselected processes, but instead to learn what knowledge the student constructs while in interaction with the teacher-researcher.

Tzur (1994) summarized the interrelated activities which takes place during a C-TE:

(a) Planning learning situations and tasks for the next teaching episode, on the basis of working hypotheses regarding the child’s zone of potential construction;

(b) conducting the video-taped teaching episodes in which a researcher interacts as a teacher with one child or a small group (2-3) of children;

(c) the teacher’s on-the-spot interpretations of the children's language and actions, leading to on-the-spot decisions concerning what situations to create, what critical questions to ask, what constraints to add, and what types of perturbation to induce; and

(d) dynamic re-formulation of teacher’s second order models concerning the children’s current knowledge, on the basis of the teacher’s interpretations to the children’s actions and language in previous episodes (p.88).

Steffe and D'Ambrosio (1996, p. 65), from the constructivist perspective, view a genuine teaching-learning process as an event in which the teacher engages in active learning as well. Teachers' learning involves the students' understanding of the subject matter and reconstruction of that understanding during the process. They make a distinction between
Piaget's clinical interview approach and C-TE by recognizing that "the clinical interview is aimed at establishing where students are, whereas the teaching experiment is directed toward understanding the progress that students make over an extended period of time" (p. 66).

Steffe, Thompson, and von Glasersfeld (2000) draw attention to researchers' getting "thoroughly acquainted, at an experiential level, with students' ways and means of operating" in the domain of interest (p. 275). They realize that interacting with students during an episode of teaching in a short period of time will not be sufficient to develop an insight about students' thinking and how it might be influenced. Such an interaction with students gives the teacher-researcher the freedom to form and test hypotheses on the spot (p. 277). Steffe, et. al. emphasize that teachers go through a period of learning as well (p. 299) which allows them to generate living models of students thinking (p. 287). Thus, "teaching experiments serve the construction of models of conceptual change" throughout a period of time (p. 299). Because the models that teacher-researchers formulate are grounded in their interactions with students, they can fully expect that the models will be useful to them as they engage in further interactive scientific communication with other students (p. 298). They state that, for such models, it is important if they somehow "fit" rather than "match" what is out there: "[t]hus a model is viable as long as it remains adequate to explain students' independent contributions. But no amount of fit can turn a model into a description of what may be going on. It remains an interpretation that seems viable from a particular perspective" (p. 302).
2.3.2 Interviewing as means of probing learning

Kvale (1996) states that the qualitative research interview is an attempt "to understand the world from the subjects' points of view, to unfold the meaning of peoples' experiences, to uncover their lived world prior to scientific explanations. The qualitative research interview is a construction site of knowledge. An interview is literally an *inter view*, an interchange of views between two persons conversing about a theme of mutual interest" (pp. 1-2). He introduces the *miner vs. traveler* metaphoric contrast to illustrate how he visualizes the role of researcher as interviewer. The miner metaphor symbolizes an objective truth to be uncovered and brought to daylight, whereas the traveler metaphor illustrates gaining experiences and insights throughout a journey which is not planned to its finest details even if a specific route was predetermined. The journey might introduce unforeseen challenges and/or lead to new explorations for the traveler. "The journey may not only lead to new knowledge; the traveler might change as well. The journey might instigate a process of reflection that leads the interviewer to new ways of self-understanding, as well as uncovering previously taken for granted values and customs in the traveler's home country" (p. 4). This is, of course, a shift from conceptualizing knowledge as a 'given' to regarding it as a 'constructive understanding.' Thus, he defines a *semistructured life world interview* as "an interview whose purpose is to obtain descriptions of the life world of the interviewee with respect to interpreting the meaning of the described phenomena" (pp. 5-6).

Woods and Thorley (1993) also agree with such a notion of interviewing and assert that interviews introduce a great potential for gaining an in-depth understanding about students' knowledge. They characterize a qualitative research study with small groups of
students as "not simply a matter of finding out what is there: It is also a coming-to-
understand of what there is to look for" (p. 26).
Chapter 3

METHODS AND PROCEDURES

Van Helsing: "We'll investigate the matter scientifically, without prejudice and without superstition."
Lucy Harker: "Enough of your science! I know what I have to do."
—Nosferatu the Vampyre
by Werner Herzog
(Morrison, 1990, p.340)

In chapter 1, I introduced the problem statement of this study (see section 1.2). In chapter 2, I explained the theoretical framework through which I am interpreting the findings of this study (see section 2.2) and reviewed some widely used techniques relevant to this study for probing understanding in qualitative research (see section 2.3).

In this chapter, I will describe the specifics of the research design of the study and detail the circumstances under which the study was conducted (i.e. background and instructional context of the study), as well as methods of investigation (i.e. data collection, instrumentation and analysis procedures). The chapter concludes with an overview of the study and a discussion on strengths and limitations of the study stemming from validity, reliability, and generalizability issues pertaining to its design.
We shall go on seeking [truth] to the end, so long as there are men on the earth. We shall seek it in all manner of strange ways; some of them wise, and some of them utterly foolish. But the search will never end.

–Arthur Machen
"With the Gods in Spring"
(Morrison, 1990, p.xx)

3.1 Design of the research study: A qualitative case study

This study was designed as an in-depth investigation of one novice college student's learning of force and motion. The data were largely qualitative in nature and drawn from several sources. Many features of this study resembled the teaching experiment methodology as described by Steffe, Thompson, and Glasersfeld (2000, pp. 267-306). In the following sections the background and the context of the study as well as methods of data collection and analysis will be explained in detail.

3.1.1 Background of the study

In spring and summer 1998 a group of faculty from the College of Education and the College of Engineering of the Pennsylvania State University designed a physical science-based engineering course, titled "Fundamentals of Science and Engineering Design," primarily for elementary education majors (Taylor, Dana, and Tasar, 1999; Tasar, Dana, Taylor, and Lunetta, 2000) in an effort "to foster students’ understanding of concepts and principles of physical science and engineering, promote scientific inquiry, problem-solving skills and an appreciation of science and technology" (Taylor, Lunetta, Dana, and Tasar, in
"The instructional strategy was designed as a practical, hands-on approach to help students develop a qualitative and quantitative understanding of [selected physics and engineering] concepts and apply the concepts to solve problems" (Taylor, Dana, and Tasar, in press). During this period, I was actively involved in the design of this course prior to its delivery.

The course was offered for the first time in the fall semester 1998, during which the design of this research study was formulated. All eleven students enrolled that semester were female elementary education majors. Throughout this semester, I acted as a co-instructor, interacting with the students and the members of the course development team. Steffe, Thompson, and Glasersfeld (2000, p. 286) emphasize that in such a case study research design communication with students can be established more easily if the teacher-researcher has a history of interactions with students similar to the participants in the actual study. Accordingly, my dynamic involvement in course development and delivery created a unique opportunity to recognize the students' level of understanding of the physical concepts and their approach to solving problems in the domain of simple machines.

3.1.2 Context of the study

This research study took place during the delivery of the course "Fundamentals of Science and Engineering Design" in the Spring semester 1999. Again, all the students enrolled were elementary education majors. The basic goal of this course was to provide future elementary school teachers an authentic experience in science and engineering, an emphasis on science concepts and problem solving skills that are important elements of
literacy in the pure and applied physical sciences and also prominent in typical elementary school curricula and standards (National Research Council, 1996).

The course consisted of three major units, all of which revolved around a progressive course project: designing and building a bridge and developing it by using the technology tools covered during each unit. Students worked in groups of 2-4 to carry out this ongoing project. Each unit typically started with discussions on concepts revealing students' preconceptions and fostering more scientific ones. In this initial period many hands-on activities were provided to the students to aid their learning. In the next phase students were expected to implement ideas from their studies to the course design project (the project was based on a scenario in which a town desires a cost efficient bridge meeting certain design specifications to be built across a nearby river. As time passes (i.e. at the end of each subsequent unit) the town faces new demands which require a more sophisticated bridge (i.e. lifting the bridge to allow taller ships to be able to pass underneath, electrifying the bridge to automate the lifting, and adding traffic lights to handle the busy traffic on the bridge).

The course began with a ‘Structures and Stability’ unit in which students explored conditions for static equilibrium, tension and compression on beams together with principles of engineering design. They utilized computer simulations to create a truss-bridge design and then built their actual model bridges using Lego™ and K’NEX pieces. This model bridge had to be 60 cm long, 10 cm wide, and any height; it also needed to be strong enough to hold at least a 5 kg load when suspended at the middle of the bridge.

The second unit of the course was 'Simple Machines.' Students in this unit studied different simple machines (i.e., ramps, wheel & axle, gears, pulleys, and levers), their use in
everyday life, and how to calculate the mechanical advantage (ideal and actual) of each of these machines and combinations of them. After this instruction on simple machines, students continued work on their bridge design project. They created ideas and implemented new parts into their original structure (i.e., they used each of the simple machines covered during the unit for tasks such as lifting the center of the bridge at least 15 cm in the most efficient manner).

The last unit of the course was 'Basic Electricity.' In this unit students engaged in activities in which they explored electric circuits and elementary concepts in basic electricity. Toward the end of the unit they returned to the ongoing bridge design project and added electrical components like buzzers (to go off before the bridge is lifted), traffic lights, and a motor to drive the simple machines mechanism.

At the end of each unit all groups presented their accomplishments in front of the whole class (who were acting as citizens of the town) and the instructors (the governing body of the town). From the instructional design point of view, the student group presentations were intended to create an opportunity for them to receive/give feedback and to learn how other groups generated and implemented new ideas and executed their projects. Instructors anticipated that preparing and delivering such presentations could foster students' effective communications skills.

3.1.2.1 Case study group instruction

After I became acquainted with the students during the first unit, the experimental instruction took place in a separate room during the second unit (Simple Machines) of the
course with four students. This was done in order to provide clinical study conditions in a naturalistic setting and to focus on a small group for investigating student learning in depth. The group met twice a week on Tuesdays and Thursdays for five consecutive weeks in the morning hours starting at 9:00 AM during the regular class times, and each session lasted two hours. All sessions were video-taped. Rather than a lecture format, a student-centered 'studio' format (Taylor, Lunetta, Dana, and Tasar, in press-a) was adopted in order to reveal and discuss students’ own ideas and help facilitate learning through active involvement and supportive classroom discourse.

Concepts of force and motion were discussed during the first three meetings for two distinct reasons: the research purpose was to elicit the participants' preconceptions about these concepts, and the instructional purpose was to foster a qualitative understanding within the domain in order to facilitate meaningful learning of subsequent topics in the unit. Inclined planes were covered in this opening period as well to explicate the concepts of force, acceleration, and velocity. This was meant to give students an opportunity to conceptually relate such basic concepts to simple machines. The instruction then proceeded with four other simple machines (levers, pulleys, wheel & axle, and gears). Considerably longer time was spent on pulleys since they are different than other simple machines in two principal ways:

i) many different combinations of pulleys can be produced, which creates an opportunity for probing students' learning of the same concepts and solving problems from different perspectives;

ii) unlike other simple machines, the mechanical advantage of a pulley system cannot always be determined from its physical dimensions. The determination of the
mechanical advantage of a pulley system requires a thoughtful examination of the mechanism itself. Therefore, discussions with students about their use of pulleys have a strong potential to provide information about the nature of learning: whether students are engaging in rote learning or developing a meaningful understanding.

The daily instructional activities that took place during this study are outlined in Table 4.1 (see section 3.1.3). Sections 4.2.2 give the details of the day-by-day instruction reconstructed from the video recordings. Examples of student participation in discussions have also been included in those sections, where appropriate and necessary. Both sections describe and exemplify the nature of student involvement in this experimental teaching class and the nature of the instruction.

### 3.1.2.2 Teacher-researcher's qualifications and roles during the study

I held bachelor's and master's degrees in physics and my main research area has been secondary and college level teaching and learning of physics. I have been an active participant and contributor at professional conferences, and I have had extensive interactions with other researchers in science education and physics education. At the time of the data collection, I had completed the course work for the degree of Ph.D. in curriculum and instruction with an emphasis in science education. I have given special attention to Cognitive Foundations of Learning Science and the History and Philosophy of Science. Prior to the beginning of this study I was well informed about qualitative research methods in general; I also studied open-ended and semi-structured interviewing techniques and had first hand experiences. My earlier scholarly work included observing a Science
Methods course at Penn State University for prospective elementary school teachers during a spring 1997 (Tasar, 1999). During this study students' in-class activities were recorded as a participant-observer. Students' views about teaching and learning science were probed by surveys and other data collected from student reports, homework, and concept-maps. I also gathered data about the nature of their earlier science learning experiences from their own testimonials.

Throughout the study, I acted simultaneously as teacher and researcher of the small 'case study research group.' Such an involvement is not unusual in qualitative research. Steffe et. al. (2000) strongly encourage researcher's involvement as a teacher during investigation and view this dual role as a potential strength of a study rather than a weakness (p. 305). Merriam (1998, p. 203) also asserts that researchers are the primary instrument of data collection as well as analysis in qualitative research. Consequently, "interpretations of reality are accessed directly through their observations and interviews" (p. 203). Which in turn brings them "closer" to reality than if a data collection instrument had been interjected between the researcher and the participants. Hence, my two roles in this study gave me access to deeper insights about the students' learning.

As researcher, I was responsible for determining types, timing, and sequence of all data to be collected. Furthermore, I was the administrator of paper-pencil tests and the interviewer for the semi-structured interviews and think-aloud sessions. As teacher, I was involved in the development of the course in Spring and Summer 1998 and the delivery in the Fall 1998 prior to actual data collection. During the first unit in the Spring 1999, I spent time with all the students enrolled in the course as a co-instructor, giving me an opportunity to become acquainted and to develop good communications with the students.
At the start of the simple machines unit, I reminded the students in the small case study teaching group that I am not a native speaker of English. I assured them that any indication of lack of understanding would not offend me in any way. Indeed, the students were strongly encouraged to ask questions to clarify things whenever they felt they did not understand the language or the subject matter.

### 3.1.2.3 Participants

In Spring 1999 a total of ten students were enrolled in the Fundamentals of Science and Engineering Design course, only three of whom were male. During the first unit of the course, Structures and Stability, students chose their own partners and worked in small groups for the course project. Towards the end of the unit the researcher approached four students who were working in two different groups to ask if they would like to participate in an exploratory small group instruction project for the Simple Machines unit. June and Mae were partners, and April and Mike were working together as well (all names are pseudonyms). They were assured that their participation would be totally voluntary and there would be no punishment for not participating or quitting at any time. They were not offered any incentives for participating (i.e., no payments or extra points towards their final course grades were offered.)

### 3.1.2.3.1. Sampling Criteria

In selecting students for the small case study instruction group my main concern was students' comfort of communication with me. For a qualitative study, which requires the
participants to express their thoughts out-loud, it was deemed extremely important that the participants believed in my complete sincerity. Hence, the level of communication, already established during the first five weeks of the semester, played a significant role for making the decision in student selection for the study.

3.1.2.3.2 Participants' background in learning physical sciences and characteristics

One of the four students who agreed to participate in this study was June, an 18 year old female freshman majoring in elementary education. Her previous experience in formal physics coursework consisted of only a seventh grade physical science course, though she took three years of biological science courses in high school. She had also taken several mathematics courses; she was enrolled in an integrated advanced math track where she learned subjects "like trigonometry and geometry and everything" and in her senior year she "ended up with calculus so.. some of the things we are getting into like the resultant force and stuff we get some of that in the calculus but no actual physics training" (excerpt from first interview on March 3, 1999, lines 5-11).

June was selected to become the main participant/character of this case study for two equally important reasons:

i) her long term availability and willingness to continue to participate

ii) her major, background, prior knowledge, the nature of her interaction with the subject matter as a beginning learner, and her ability to verbally express her ideas to the researcher.
June maintained a good relationship with me throughout the three semester study. According to my observations during this period, she is a meticulous, punctual, sincere, and trustworthy individual and a hard-working student with continued enthusiasm to carry out course tasks properly. June has been a student with a high grade point average (3.96 overall GPA at the conclusion of this study). It is important to note that even in semesters that followed the Spring 1999, when the instruction had taken place, she responded promptly and kindly to my requests for additional interviews without any expectations of monetary gains. For the post-instructional interviews she was informed about a small monetary incentive only after she had agreed to participate in further interviews. Since the interviews took place outside the classroom sessions her only concern was to schedule them in a timely manner, so as not to interfere with her other activities.

Mac, April, and Mike, the three other students in the case study instruction group, were in their junior years and were also majoring in elementary education. Mac took chemistry courses in high school and an introductory physics course for students in non-technical fields at Penn State. She described the physics course as follows: "I guess a lot of it was like astronomy, Newton's laws, and just basic concepts. 'Physics for coeds' is what they call it." On the other hand, neither April nor Mike reported that they had taken any physics/physical science courses in junior high school, high school, or in college until the Spring 1999 when they enrolled in the course where the study was conducted.
3.1.2.3.3 Participants' cognitive dispositions: Field-dependence/independence

Cognitive styles are constructs that help us understand some aspects of individual differences. However, the existence of a number of such styles should not cause confusion. Rather than viewing different cognitive styles as rival or mutually exclusive psychometric techniques, it is healthier to regard them as different ways of describing individual differences each with its own internal validity. The researcher chose to include the Group Embedded Figures Test (GEFT) as part of the data in order to learn about the participants' cognitive styles solely as a general descriptive element of their cognitive dispositions as revealed by the construct field-dependence/independence.

Towards the end of the experimental instruction the students were given the GEFT (Witkin, Oltman, Raskin, and Karp, 1971) in order to evaluate their cognitive style. "... Cognitive styles are the characteristic, self consistent modes of functioning which individuals show in their perceptual and intellectual activities." (Witkin, et. al., 1971, p. 3). The GEFT is an assessment instrument for the styles field-dependence and field-independence. The relevance of this construct to student learning in science was discussed in section 2.1.6

I was well informed about the field-dependence/independence construct at the time the GEFT was administered to the participants, and prior to the time that they took the test I had not noticed any significant differences in their learning patterns pertaining to field-dependence/independence. The students' GEFT scores did not play any role in my decision making in subsequent phases of the study.

The students' GEFT scores in this study were determined as follows: June 13, Mike 12, Mae 11, and April 8 (maximum 18). When compared to the norms published by Witkin,
et. al. (1971, p. 28) June's score fall into the third quartile, Mike's and Mae's into the second quartile, April's into the first quartile. These results suggest that all of the participants' cognitive styles can be identified as field-dependent in relatively varying degrees; although non of them was highly field-independent, April was highly field-dependent. June's relatively high score as compared to the rest of the group means that along the continuum between high field-dependence and high field-independence, her cognitive disposition probably lies around the transition point. Her score reveals that although she is not extremely field-dependent, like April, she does not posses the characteristics of extremely field-independent individuals either. The participants' choice of elementary school teaching as a career, their choice of mostly non-science subjects in their schooling (since they were less interested in learning science), and their way of learning in general appeared to the researcher to be congruent with their GEFT scores. Section 3.1.4.1 describes how the GEFT test was administered to this group of students.

### 3.1.3 Methods, Instruments, and Procedures of Data Collection and Analysis of Data

Methods, instruments, and procedures of data collection for this study were selected for their ability to:

i) describe the participants,

ii) describe the contextual/instructional setting,

iii) describe the interactions that took place between the participants and the instrument, and between the participants and the researcher,

iv) probe student understanding and learning in-depth in a case study.
Hence, the data collected for this study were largely qualitative in nature. The sub-sections below explain in detail methods and procedures of data collection and the instruments used (i.e., the GEFT, word association task, content specific paper-pencil tests, audio recordings of interviews, video recordings of classroom sessions, and student artifacts). Additionally, each sub-section includes a description of how the data were processed and analyzed.

3.1.3.1 Group Embedded Figures Test (GEFT)

The GEFT has been proposed as a convenient substitute for the Embedded Figures Test (EFT) when the test is to be administered to a group of subjects rather than to individuals. Witkin et. al. (1971, p. 28) reported that the reliability estimate of the GEFT was .82 and its validity was well-established (i.e., the GEFT highly correlated with the criterion measures: the EFT and the rod-and-frame test).

The GEFT has 3 sections and 25 items. The seven items in the first section are very simple and are not included in scoring since they are intended for practice. The second and third sections each contain 9 more difficult items that are scored. On March 23, 1999 the GEFT was administered to the students during class after an introductory briefing on the test. The test was administered and scored strictly according to its guidelines as suggested by Witkin, et. al. (1971, pp. 27-28). Two minutes were allocated for the first section and 5 minutes for each subsequent section. Overall, the administration of the GEFT took less than 20 minutes.
I scored the test following its administration according to the scoring key provided by the authors. The authors also provided norms based on men and women college students from an eastern liberal arts college. They indicated that "these norms are strictly applicable only to individuals coming from populations similar to the group from which the norms were obtained. For other populations, they can serve only as a general guide." (Witkin, et. al., 1971, p. 28).

3.1.3.2 Word association task

Word association in relation to knowledge organization/cognitive structure was reviewed in chapter 2 (section 2.1.4). As part of my triangulation strategy, I chose to administer a word association task at the end of the unit to all of the students enrolled in the course in order to probe the knowledge structures they held (i.e., quality and quantity of associations made formed by the students between selected concepts introduced throughout the unit). In this particular administration I followed the guidelines given by White and Gunstone (1992, pp. 142-157). Twelve stimulus words were chosen for this task according to their deemed significance in capturing the students' knowledge organizations regarding simple machines (e.g., lever, pulley, load, etc.) as well as a few basic mechanics concepts (e.g., force, acceleration, etc.). Seventy five seconds were allotted to respond to each stimulus word.

In order to administer this task, I designed a 28-page booklet printed on thick colored paper that did not allow its other side to show through. Students wrote their names and the date on the cover page; the second page contained instructions and an example of a
completed word association task taken from White and Gunstone (p. 143, see Figure 3.1). Each pair of facing pages was used for one stimulus word, with the left hand side presenting the stimulus word and the right hand side left blank. Each left hand page contained one stimulus word written in capital letters at the top of the page and twelve lines beginning with the stimulus word on that page (see Figure 3.2).

The researcher paid special attention to the "prompting effect" while designing the booklet. Rather than words that are interchangeably used in daily language (e.g. load, mass, and weight or work, effort, and force) following each other, they were deliberately ordered in a way to resemble a random pattern so as not to cue those similar words in students' memory. The stimulus words were presented in the booklet in the following order: Work, load, acceleration, vector, tension, pulley, mass, force, mechanical advantage, lever, weight, and effort.

I converted the students' responses, which were in the form of a list of words for each stimulus word, to a summary representation as a visual aid to portray the relationships created by the students (see Sections 4.2.7) Then, rather than analyzing the associations numerically as suggested by White & Gunstone (1992, pp. 153-154), I used a descriptive approach: responses were analyzed according to the presence or absence of links between specific stimulus words and functional resemblances between words in the response lists for the stimuli, even if the same word did not appear in both lists.
**Instructions**

This is a task to explore what ideas you link together in your minds within the topic of **simple machines**. On each page in this booklet one keyword is introduced. For each keyword write all the words it makes you think of. If you do not fill all the spaces provided, do not worry; just put in as many words as you can. Put only one word on each line.

Below is an example from a study. In that study the topic was **ceramics**. One respondent associated the following words to the given keywords (*in italics*):

<table>
<thead>
<tr>
<th>clay</th>
<th>porcelain</th>
<th>glazed</th>
<th>pottery</th>
<th>kiln</th>
</tr>
</thead>
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<td>mud</td>
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<td>glass</td>
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<td>shape</td>
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<td>color</td>
<td>selling</td>
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<td>pots</td>
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<td>white</td>
<td>waterproofing</td>
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<td>smooth</td>
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<td>glazes</td>
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<td></td>
<td></td>
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<td>bricks</td>
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</table>

This is a timed task. Please proceed to the next page when the instructor tells you to do so each time.

Please ask questions you may have at this time.

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Figure 3.1. The instructions page of the word association task.

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**WORK**

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Figure 3.2. A sample page from the word association booklet, prepared by the researcher, which shows how the stimulus words were presented.
3.1.3.3 Paper-pencil content tests - Development and administration

The experimental instruction for the study took place in fifteen sessions during a five week period. I administered paper-pencil tests three times: during the first, eighth, and thirteenth sessions (see Table 4.1 and section 4.1 for the chronology). Paper-pencil tests also served to triangulate methods of data gathering.

The purpose of the first test was to probe the students' initial understandings when they started the unit; the second test was more like an individual problem solving session tutored by the teacher/researcher. The third was a content assessment test administered at the end of the unit which was prepared by the main course instructor and given to all students enrolled in the course. Students were asked to provide extended responses to the questions in these tests, even for multiple choice items. Their responses to the questions in these tests proved to be a valuable form of data when coupled with other data since the responses represent, chronologically, the progression of the students' understanding and learning in written form and in their own words.

I utilized my knowledge of the subject matter, my previous experiences, and various textbooks when designing the first two tests. The third, the unit content assessment test, was prepared by the main course instructor with my approval for appropriateness to the students, since the two instructors had followed different agendas for teaching the 'Simple Machines' unit. I also administered the "Force and Motion Conceptual Evaluation" test (Thornton & Sokoloff, 1998) during one of the post-instructional interviews to June on March 31, 2000 as part of my data triangulation strategy (she took this multiple choice test.
by herself without any intervention and then responded to my additional questions to further clarify her point of view).

Written data, such as June's responses to paper-pencil tests, were coded and analyzed for the purpose of uncovering the nature of her conceptual understanding and development. Categories pertaining to her learning emerged from the data as new data became available. Since the purpose of this study was to depict one student's learning of a physics topic in a comprehensive way rather than, for example, identifying what misconceptions she had held at the time, it was utterly important to be able to present the progression of her learning. For this reason data will be presented in chronological order in chapter 4, but the analysis and interpretation will rest on emerging patterns stemming from a careful consideration of different sources and forms of data altogether.

3.1.3.4 Preparing and conducting the clinical-tutoring interviews

Another method of data collection in this study was clinical-tutoring interviews. The place and importance of interviews as means of data collection were presented in section 2.2. The participants of this study were interviewed by the researcher during the instructional unit as many times as possible according to their availability: June, April and Mike twice each, and Mae once. All interviews were audio-taped (see Table 4.1 and sections 4.1). Although they were offered no incentives for giving interviews during this period, June was paid $10/hour for the post-instructional sessions in which she participated during spring semester 2000.
The research questions and ongoing classroom discussions guided the content of the tutoring-interviews. I always prepared a flexible plan for each interview session in advance, including an agenda and ways of conversing with the participant about the subject matter. Often times I also prepared a worksheet for the participant to respond to which resembled more of a think-aloud protocol for the interview. Thus, the interviews can be characterized either as semi-structured clinical interviews or as think-aloud sessions.

Each interview took typically 1-1.5 hours. When an interview lasted longer than intended, I modified the interview plan while in progress, giving immediate conscious decisions to fit the available time, or giving priority to the parts deemed important, postponing others. Planning of the interview sessions (i.e., what to ask and how to conduct the interviews) depended upon the students' previous responses in earlier sessions. In short, the interviews were semi-structured in nature and I did not have a step by step determined plan for the interviews to strictly follow. I created, adapted, or selected test items/instruments to be used during interviews as worksheets, according to the study's progression. This is another point which shows the importance of my role and critical presence during this study.

I selected a small group instruction as the method of this research study to facilitate in-depth investigation of the students' learning processes and to obtain vivid, thick, and rich descriptions of these processes. Hence, the purpose of the interviews was to collect further complementary data on what the students were thinking about the concepts covered during instruction. Thus, conducting one-on-one interviews gave me a unique opportunity to investigate interactively and dynamically the students' learning processes and to understand the ways the participants were thinking and reasoning about the physical phenomena. In
other words, interviews were regarded as a means of "seeing" the phenomena through the students' eyes, since observing and interacting with the students while they are engaged in conceptually challenging tasks help reveal their modes of thinking at that point in time.

I transcribed all interview tapes verbatim to avoid overlooking any significant point during analysis. Chapter 4 contains excerpts from interview transcripts together with interpretations and analysis. These portions were selected after the analysis to represent the key points of the student's learning. Since data in this study were collected from multiple sources by using various methods, I sought convergence (different bits and pieces pointing out the same or similar finding) in the data. Therefore, during interpretation the data were evaluated completely.

3.1.3.5 Video-tapes of classroom sessions

All classroom sessions during the research study were video taped. A camera was set at the back of the classroom before the students arrived and was kept running during the whole of each session. This was done in order to obtain an accurate record of what happened during instruction for future reference. Sections 4.2.2 include episodes from each session reconstructed by the researcher using these video recordings. As will be seen in those sections, these recordings of the conversations between the students and me served as a valuable source of information in disclosing the students' predispositions regarding the topics covered and vivid examples of their thinking and learning.

Video-tapes were used to reconstruct what happened during instruction. For this purpose, I selectively transcribed portions containing conversations which portray the
students' conceptions, learning, and struggles during instruction. These portions were included in a summary for each instructional session describing the session from beginning to end including the topics, activities, and interactions that took place.

3.1.3.6 Student artifacts

The students who participated in the small group research instruction were asked to write a brief journal entry each week about what they learned and understood. During the tutoring interviews, June's notes, writing, and drawing were also used as supplemental data.

3.2 Characteristics of the study

Thus far the methods and procedures employed in this study have been described in detail. In this section characteristics of this study will be presented based on McDermott's (1983, p. 140) descriptive framework which captures the essential points in describing a research study. Originally, eight dimensions were used in her framework. Each of the dimensions comprised "a continuum representing a characteristic that can be used to describe a particular aspect of the research. The dimensions, which are not totally independent of one another, can vary between two extreme values for the characteristic. It is possible to characterize a given investigation by placing it somewhere along the continuum for each of the dimensions" (McDermott, p. 140)

Figure 3.3 is a modified version of McDermott's (1983) descriptive framework as it applies to this study; it portrays the characteristics explicated in this sub-section in a representational form. Here, the framework is introduced with the addition of the
"participants" dimension and more descriptors for other dimensions. The position of the checkmark along each line in the figure shows how this study can best be characterized according to that dimension. It represents proximity to an end with respect to other dimensions and by no means is absolute. If a checkmark is placed at an extreme end, it implies that this study can solely be characterized by that descriptor/quality; otherwise, it implies some combination of the two extreme values. For example, the selection of the participants is indicated as being purely purposeful by placing the checkmark at the far left end of the line (see Figure 3.3). If the checkmark were placed somewhere in between, it would imply that there were groups of participants selected both purposefully and randomly. In such a case the proximity of the checkmark to an end would imply how strongly this study relied on that group of participants. Likewise, being farther away from an end means less association with that descriptor/quality.

In addition to representing a continuum, another feature of each dimension is that the left hand side represents more engagement either from the researcher's or the participants' part as compared to the right hand side. For example, selective transcription requires more judgment during the process than verbatim transcription, which is mostly mechanical. The former has to be done by the researcher himself while the latter can be performed by anyone since it entails little judgment. Also, analyzing the data for specific conceptual difficulties requires more effort than simply cataloguing student misconceptions. Similarly, implementing open-ended tasks requires more engagement on the students' part as opposed to highly constrained tasks which are done according to a recipe.
### Descriptive Framework of the Study

<table>
<thead>
<tr>
<th>Degree of investigator/participant interaction</th>
<th>Non-interactive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interactive</td>
<td></td>
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<tr>
<td>Active</td>
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<table>
<thead>
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<th>Passive</th>
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<tbody>
<tr>
<td>Nature of participant/instrument interaction</td>
<td>Passive</td>
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</tbody>
</table>

<table>
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<th>Random Sampling</th>
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<td>Focus on large groups</td>
</tr>
<tr>
<td>Focus on individuals</td>
<td>Focus on large groups</td>
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<table>
<thead>
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<td>Natural</td>
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<table>
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<tr>
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<th>At a given time</th>
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<tbody>
<tr>
<td>Time of day</td>
<td>At a given time</td>
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<table>
<thead>
<tr>
<th>Depth of probing</th>
<th>One instance/concept</th>
</tr>
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<tbody>
<tr>
<td>Several instances/concepts</td>
<td>One instance/concept</td>
</tr>
<tr>
<td>Sequence of questions/concepts</td>
<td>Single concept/concept</td>
</tr>
<tr>
<td>Considered response</td>
<td>Initial student response</td>
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<thead>
<tr>
<th>Form of data</th>
<th>Multiple choice tests</th>
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<tbody>
<tr>
<td>Extended response writings</td>
<td>Multiple choice tests</td>
</tr>
<tr>
<td>Researcher made tests</td>
<td>Standardized tests</td>
</tr>
<tr>
<td>Selective interview transcripts</td>
<td>Verbatim interview transcripts</td>
</tr>
<tr>
<td>Selective transcripts of video recordings</td>
<td>Verbatim interview transcripts</td>
</tr>
<tr>
<td>Open-ended: Artifacts represent students' own perspective for the task</td>
<td>Constrained: Artifacts represent adherence to instructor's guidelines</td>
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<table>
<thead>
<tr>
<th>Analysis of data</th>
<th>Cataloguing of misconceptions</th>
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<tbody>
<tr>
<td>Analysis of learning &amp; conceptual difficulties</td>
<td>Cataloguing of misconceptions</td>
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<tr>
<td>Ongoing/Cyclic</td>
<td>One time</td>
</tr>
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<td>Qualitative</td>
<td>Quantitative</td>
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<table>
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<th>Showing existence of certain misconceptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model &amp; nature of student thinking &amp; learning</td>
<td>Showing existence of certain misconceptions</td>
</tr>
<tr>
<td>Hypothesis building</td>
<td>Hypothesis testing</td>
</tr>
<tr>
<td>Exploratory, descriptive, and explanatory</td>
<td>Confirmative</td>
</tr>
</tbody>
</table>

Figure 3.3. Descriptive framework of the research study which illustrates the characteristics along nine dimensions (adapted from McDermott 1983, p.140).
3.1.5.1 *Degree of investigator/participant interaction*

I interacted with the students to a great extent both before and during the study in my dual role as co-instructor of the course during the first unit (five weeks) and sole teacher for the case study group. I planned each step of the instruction and data collection: a) designed and delivered a unit on simple machines to the participants with a brief introduction to selected Newtonian concepts; b) designed or selected appropriate psychometric and content specific paper-pencil tests and administered to the participants himself; c) planned and conducted interviews with the students. See sections 3.1.1, 3.1.2.1, 3.1.4.4, 3.1.4.5, 4.1, and 5.1 for further details on the nature of investigator/participant interaction.

3.1.5.2 *Nature of participant/instrument interaction*

As opposed to those in purely observational methodologies, data collection procedures used in this study required the participants' active engagement (see section 3.1.4) since this study was conducted under clinical conditions in a simulated natural environment (see section 3.1.5.4). Although, for example, video recording itself may be seen as a passive interaction with the instrument, the participants' presence and involvement in the instruction made the study dynamic in nature. Therefore, the simulated circumstances in the classroom should be regarded as an instrument rather than the video camera. Moreover, I was also an important data gathering instrument in this study (see section 3.1.2.2), interacting with the students to a great extent as explained above (see section 3.1.5.1).
3.1.5.3 Sampling and focus

This study was designed as an in-depth investigation of student learning in physics. For that reason, I wanted to focus on learners in a small group comprised of novices, preferably in their early stages of learning physics. The course "Fundamentals of Science and Engineering Design" (see section 3.1.2 for a brief description) provided a convenient opportunity for conducting such a study since it was designed and intended primarily for elementary education majors who generally have little or no experience in learning physical sciences. A purposeful sample was selected among the students enrolled in this course (see section 3.1.2.3 for more details on participant selection criteria and procedure). The participants can be characterized as a typical sample (Merriam, 1998, p.62) since they reflected attributes of the average student majoring in elementary education. They did not reflect "in any major way atypical, extreme, deviant, or intensely unusual" (Patton, 1990, p.173) characteristics.

3.1.5.4 Contextual setting

This study took place while the participants were enrolled in an introductory physical science course at a large public northeastern university. The students knew they would be assessed and graded by the instructor of the course, who was teaching the main group, with regard to the subject matter that was to be covered during the Simple Machines unit. The instructional pedagogy employed during the study was congruent with the main philosophy of the course and was no different than that of the first unit which was delivered to all
students enrolled in the course together. The pedagogical stance was to enable the students to engage actively in their learning.

On the other hand, because the purpose of the small group research instruction was to focus on individuals more closely, I had the freedom to create my own agenda for the instructional unit and to alter this according to the perceived needs of my four students. Additionally, I created frequent opportunities for data collection rather than waiting for them to come up naturally. For instance, I video-taped the instructional sessions, administered several paper-pencil data collection instruments, and audio-taped clinical interviews, giving the research study a clinical investigation aspect. In addition, during and after the instruction, I conducted several clinical interviews which gave rise to the investigative nature of the study. My creation of a controlled environment within an already existing learning habitat indicates that the physical setting of this study included elements of a naturalistic environment in a mostly investigative one.

3.1.5.5 Temporal setting

The study lasted approximately 14 months starting with the administration of the pre-test to the last day of data collection (see section 4.1 for the chronology of data collection and instructional activities that took place during study). This research, then, bears the characteristics of a longitudinal study.
3.1.5.6 Depth of probing

Throughout the study, I collected data through multiple sources and methods at several different times to probe the students' learning of different concepts; I also used a follow-up strategy to gain deeper insights about the students' course of learning. With the exception of the word association task and the GEFT (both of which called for immediate reaction to the stimuli), the students provided considered responses to the written tasks.

3.1.5.7 Form of data

The data for this study were largely qualitative in nature and included: a) before, during, and after the instructional unit extended responses to the tests prepared by the researcher; b) standardized multiple-choice tests; c) open-ended tasks; d) verbatim transcriptions of audio recordings of interviews with the students; e) narrations and selective transcriptions of video recordings of classroom sessions; and f) student artifacts such as journal entries. Section 3.1.4 gives details of methods of data collection and instrumentation.

3.1.5.8 Analysis of data

The data were analyzed to illustrate and describe a single student's journey of learning, rather than finding out the number and/or the types of misconceptions that a group of students held. Determining the student's preconceptions helped establish her baseline knowledge. Special attention was paid to the nature of her misconceptions and how she made sense of newly emerging meanings out of discussions. I analyzed the data as they
emerged; this helped me to plan for the up-coming phases of the study. The conceptual change literature and the human problem solving literature were utilized to interpret the findings.

3.1.5.9 Point of view of investigator

The theoretical framework of the study was defined in section 1.1 and further elaborated in section 2.1. In brief The point of view put forth was i) learners are not "empty vessels" – they come to learning environments with all sorts of different prior knowledge which plays an important role in subsequent learning; ii) novices' preconceptions are persistent and often quite different than those of scientists'; iii) they possess small functional units of knowledge, build naïve representations, categorize based on surface similarities, and work backwards from unknowns to givens while solving problems.

The purpose of this study was to gain insights into dynamics of students' thinking, reasoning, and learning rather than determining what specific misconceptions existed, and/or were persistent. I did not aim to prove or disprove the effectiveness of specific instructional strategies, a task well beyond the realm of case studies. Rather, the aim of this study was to depict a case of a learning process with possible successes and failures along the way and to evaluate the process in its entirety to develop an understanding of how the different parts might contribute to the whole. To that end, I investigated a single case as thoroughly as possible to support any achievable conclusion for the case and to generate hypotheses by direct observational evidence rather than by indirect inference. Hence, this
study can best be characterized as 'exploratory, descriptive, and explanatory' rather than 'confirmative.'

When you cannot measure it, when you cannot express it in numbers, your knowledge of it is of a meagre and unsatisfactory kind.
–Lord Kelvin (1824-1907)  
(Morrison, 1990, p. 591)

3.3 Methodological design issues: Strengths and limitations of the study

Science is a means to generate knowledge. This is an underlying assumption of the scientific enterprise, if not the definition. According to Popper (1959), empirical science can be distinguished by three criteria:

- the system called 'empirical science' is intended to represent only one world: the 'real world' or the 'world of our experience'. … we may distinguish three requirements which our theoretical empirical system will have to satisfy. First it must be *synthetic*, so it may represent a non-contradictory, a *possible* world. Secondly, it must satisfy the criterion of demarcation, *i.e.* it must not be metaphysical, but must represent a world of possible *experience*. Thirdly, it must be a system distinguished in some way from other such systems as the one which represents *our* world of experience. (p. 39, all italics are original.)

But, what is the nature of knowledge that is achieved through science? How can one be sure that a scientific conclusion entails to what it is ascribed, is either personal or can be authenticated by independent parties, or is either local or universal? In this sense, all research studies, regardless of their methodology, are subject to scrutiny. They all must account for 'how and under what conditions was the study conducted?' and 'how the data were analyzed to arrive conclusions?'
In this chapter, methods and procedures of data collection were explicated in detail. The actual data together with their analysis and interpretation are presented in chapters 4 and 5. This section attempts to answer the questions "how were the validity and reliability of this study ensured?" and "what are the strengths and limitations of this study in terms of its methodology?"

These concerns can be exemplified more specifically as follows: If I am observing an occurrence of a phenomenon, then,

1. Is what I "think" I am "seeing" really what is actually happening?
2. Does/will everyone "see" it the same the same way I do?
3. Can I define the general characteristics of this phenomenon by my perceptions only?

These questions relate to the internal validity, reliability, and external validity respectively of "observing a phenomenon."

"Beauty is in the eye of the beholder."
–English proverb.

3.2.1 Internal Validity: Reality check

While acknowledging that there is no hard-rock ultimate foundation for ethnographic interpretation and that "cultural analysis is essentially incomplete" (Maxwell, 1996, p. 87), for qualitative research, Maxwell (pp. 4-5) conceives validity as:

- how might the researcher be wrong;
- what are the plausible alternative explanations and validity threats to the potential conclusions of the study, and how the researcher deals with them;
how do the data that the researcher has, or that she/he could collect, support or challenge the researcher's ideas about what's going on; and

- why should everybody else believe the researcher's results?

In broad terms validity refers to "the correctness or credibility of a description, conclusion, explanation, interpretation, or other sort of account" (Maxwell, p. 87). As Merriam (1998) describes, these are concerns about **internal validity** defined as the match between what a researcher declares he/she has observed and the reality, given that an objective reality exists.

In the context of this study, internal validity can be translated as whether my accounts about June's preconceptions, learning process, and problem solving really match what she had demonstrated or could demonstrate, or are there certain kinds of threats that might have interfered with the data collection, analysis, and/or interpretations? Additionally, what sorts of precautions were taken against such possible threats while conducting the study? The remainder of this section addresses those concerns as they pertain to this study.

Maxwell asserts that three types of understanding emerging from a study – namely descriptive, interpretive, and theoretical – introduce distinct threats to validity (p. 89):

i) **Description.** *Were the data recorded accurately and completely?* Previously in this chapter, data collection methods were described in detail (i.e. video recording during instruction, audio-taping during interviews, etc. For a quick reference see figure 3.3). The data for this study were collected in the most comprehensive way deemed possible and reasonable to make sure that subsequent analysis and interpretations rest on sound evidence. When transcribing audio and video tapes a sincere effort was put forth to accurately reflect the recordings. Whenever an inaudible segment was encountered it was indicated as such.
ii) Interpretation. Whose voice dominated: the researcher's or the participant's? Being aware of this threat, I used extra caution and spent extra effort throughout the study to avoid imposing my own meanings, focusing instead on understanding June's perspective and the meanings she attached to her own words and actions. Throughout the interviews open-ended questions were asked and often more clarification was sought on her responses so as not to leave much room for speculation during analysis and interpretation. Leading and ambiguous questions were avoided. Also, her own accounts were sought regarding her learning, a strategy called member checking (Maxwell, p. 94; Merriam, p. 204).

Moreover, during this study, data were collected from various sources by various methods, at different times, over a long period of time. This helped reduce the risk of my voice becoming dominant since more direct evidence leaves less room for interpretation. This process is called data triangulation (Maxwell, p. 93-94; Merriam, p. 204; Patton, 187; Lincoln & Guba, 1985, p. 283). From the definitions in the literature (Lincoln & Guba, 1985, p. 305; Patton, pp. 187-188), data triangulation can be illustrated as searching for a spot by a method that can only reveal in which direction it lies from the observer. Since the distance of the point to the investigator is not known it can be virtually anywhere on the line that extends to infinity in the direction determined. However, if there is a second source of information of the same sort (i.e., direction with respect to a second observer), then the exact position of the point can be found at the intersection of the two lines originating from the two observers (i.e., sources) in the specified directions (see Figure 3.4). This is called triangulation of data sources.
In this study, I collected data using several sources at different times on the same subject. This is best demonstrated by the data that came from repeated interviews and several paper-pencil tasks. The purpose was to ensure that June's response at one time wasn't just due to a coincidence, but rather accurately reflected what she really meant. Thus, a convergence in the data to the same conclusion would mean the data were being gathered properly. Otherwise, it would indicate a need for further investigation.

Data triangulation can also be conceived as locating a specific point with respect to a landmark by knowing the distance only. If a point is defined only by its distance from a single landmark, then it can be anywhere on a circle around the landmark with the specified radius (see figure 3.5.a). In this case all points on the circle have equal chances of being the correct one that no preference can be ascribed to any single one of them over others. To be
more precise, two landmarks can be chosen to define the location of a point. Then, the location can be at two equally likely points (i.e., circles around the two landmarks will intersect at two points only, see figure 3.5.b). In the case of existence of three landmarks, not laying on a line but forming a triangle, a location can be uniquely defined with respect to its distance to each of these three landmarks (the circles around the landmarks will intersect at one and only one point, see figure 3.5.c). If the distances to more than three landmarks from the location of a point are known then this further reduces the chance of making measurement errors in locating the point if the error is not of a standard type. This is also a triangulation of data sources as described above, but in this case by a different method.

Employing these two methods of finding the location of a point, namely by distances and from directional orientations, provides another type of triangulation called triangulation of methods. Therefore, using a variety of data sources and methods further increases the credibility of a study (Lincoln & Guba, 1985, p. 307). Figure 3.6 illustrates the relationship between sources and methods of data collection, and analysis in this study.
Figure 3.5. Conceiving data triangulation. a) Locating a point by distance to a single landmark. It can be anywhere on the circle. b) Locating a point with respect to two landmarks reduces the chance of making errors. c) A point can be located uniquely if the distances to three landmarks are known.

Figure 3.6. Data triangulation in this study (adopted from Duschl, 1983). Data were collected from several sources through different methods (see section 3.1.4).
Furthermore, I remained open-minded throughout the data collection, analysis, and interpretation phases of the study, avoiding the undue influence from the reported findings in the current literature or even my own preconceptions of the phenomenon under investigation. This open-mindedness allowed me to carefully listen to the participants and capture the meanings of their responses rather than molding them into existing patterns in the literature. For example, the data analysis in chapter 4 reveals that I was paying enough attention, both during data collection and interpretation, to capture June's particular difficulty understanding force and motion, which, to best of my knowledge, has not been reported in the literature to this date. After identifying this difficulty, I investigated the issue in-depth by means of data triangulation and established that her struggle laid in understanding variable rate of change of a quantity. Based on June's responses, a diagnostic instrument was developed (see section 4.2.1) which is an outcome of this research study that has also been used as a data collection instrument (a similar account was described by Taber (2000) in his case study report in the domain of chemical bonding). This shows that, although I had a focused research agenda I was able to keep from imposing my own understanding of the subject matter and meanings, focusing instead on what the participant had to say.

iii) Theory. How did the researcher evaluate data? To begin with, this study was 'something meaningful, and something worth doing' for me. I had a plan for the investigation even before it began (i.e., novice college students' learning of physical science). Also, the study was conducted under modified naturalistic conditions and had strong indications of clinical investigation. Therefore, whatever data emerged from this study was not completely random, indicating I did not enter a naturalistic setting such as those encountered in ethnographic or participant observation studies. Rather, I purposefully selected a setting (i.e. a college level
course for beginner physical science students) in which I hoped to observe certain types of behaviors related to student learning (e.g. the effect of student preconceptions on learning), but one in which I could also create opportunities for them to surface (i.e. acted as the instructor of the case study group and had full control over the design and the delivery of the unit). Even though the same set of data can be analyzed from many different perspectives (e.g. group dynamics of learning, nature of discourse between the participants, etc.), my purpose was to investigate in-depth one student's progression of learning.

Here a distinction must be made: having a theoretical framework is different than tampering with the data knowingly or unknowingly. That is, one can choose to look at the data from a certain theoretical viewpoint but still look for emerging, possibly new, meanings by fitting a model or theory to whatever data is attained rather than fitting the data strictly to an existing theory to show that the theory holds (Steffe, Thompson, and Glasersfeld, 2000, pp. 298-300). Therefore, researcher "washing her/his mind clean" (Taber, 2000) should not mean that the researcher cannot have any theoretical orientation. Indeed, Merriam (1998) asserts that

> what makes the case study work 'scientific' is the observer's *critical presence* [italics added] in the context of occurrence of phenomena, observation, hypothesis-testing (by confrontation and disconfirmation), triangulation of participants' perceptions, interpretations and so on. (p. 200)

In sum, I made every effort to present the data as it emerged and related to the participant's own reality without imposing my own prejudices or preferences. The purpose of this study was to portray June's learning process in its entirety. Data analysis, interpretation, and conclusions were strictly dissociated from the data in their presentations.
Table 3.1 presents important questions associated with internal validity and the researcher's answers as they relate to this study.

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Were the data collected properly?</td>
<td>YES</td>
</tr>
<tr>
<td>Were the data sources triangulated?</td>
<td>YES</td>
</tr>
<tr>
<td>Were the data collection methods triangulated?</td>
<td>YES</td>
</tr>
<tr>
<td>Was a &quot;member checking&quot; strategy implemented during data collection?</td>
<td>YES</td>
</tr>
<tr>
<td>Were the data thick, rich, and deep?</td>
<td>YES</td>
</tr>
<tr>
<td>Were the data presented in its entirety?</td>
<td>YES</td>
</tr>
<tr>
<td>Were all the available data analyzed?</td>
<td>YES</td>
</tr>
<tr>
<td>Were any part of the data overlooked or discarded during analysis?</td>
<td>NO</td>
</tr>
<tr>
<td>Were only the data that fitted the researcher's theory or point of view selected?</td>
<td>NO</td>
</tr>
<tr>
<td>Was a reality constructed as the researcher wanted to see it?</td>
<td>NO</td>
</tr>
<tr>
<td>Was the researcher's purpose to prove or disprove a theory?</td>
<td>NO</td>
</tr>
<tr>
<td>Were the participants free to act and converse naturally throughout the study?</td>
<td>YES</td>
</tr>
<tr>
<td>Were the participants constrained to act or respond in only certain ways throughout the study?</td>
<td>NO</td>
</tr>
</tbody>
</table>

"Bir çiçekle bahar gelmez."
(Spring doesn't come with a single blossom.)
–Turkish proverb.
I know by my own pot how the others boil.
–French Proverb

3.2.2 “Reliability”

Reliability is often referred to as replication of both methods and results of a study. In the physical sciences, for example, when a specific substance displays certain properties under certain conditions, it is understood that the same substance all over the universe will display exactly the same behavior under the same conditions (classical paradigm's notion of "representativeness of population," Lincoln & Guba, 1895, p. 297). Thus, reliability is
established when separate groups of scientists concur on their observation of identical behavior under the stated conditions; the case is then closed since this process is assumed to show that no systematic or random errors were involved in the originally reported experiment.

Reliability of a study related to human behavior can be established in a similar fashion: by determining that the results of a study do not depend on the investigator, but could be obtained if any other investigator conducted the same study. As indicated earlier, the same setting can be studied from different approaches by different investigators, or even the same set of data can be examined for different purposes. However, our concern is that given the same setting (i.e., the same conditions, the same environment, and the same participants), could an independent investigator find the same responses and arrive at the same conclusions? (Bogdan and Biklen, 1992, p. 48; Yin, 1994, p. 36). This is done in order to make sure that the results are not due to some random occurrence, but can be attained consistently.

Merriam (1998, p. 205) points out that traditionally "reliability refers to the extent to which research findings can be replicated. In other words, if the study is repeated will it yield the same results?" (Italics added). Nevertheless, in social sciences, qualitative research is focused to "describe and explain the world as those in the world experience it" rather than isolating the laws of human behavior (Merriam, p. 205). Singling out causes that lead to specific effects for human behavior (human learning in this case) is a highly positivistic orientation, much like believing that objective truth exists independent of the observer. The problem associated with establishing reliability of a study in the social sciences is that creating the same conditions as in the original study is never possible. Identical settings
cannot be constructed, and most importantly, the participants can never be identical, either (i.e., representativeness of population can not be easily ensured). Additionally, since the researcher's presence in the field and involvement in data gathering is critical "all reports of personal experience are not necessarily unreliable, any more than all reports of events witnessed by a large number of people are reliable" (Merriam, p. 206). The researcher himself/herself often times serves as the most important instrument in data collection. Thus, the points of view and insights brought to and created in the field by the researcher contribute a great deal to the outcomes of the study.

According to Yin (1994, p. 36), "the objective is to be sure that, if a later investigator followed exactly the same procedures as described by an earlier investigator and conducted the same case study all over again, the later investigator should arrive at the same findings and conclusions. (Note that the emphasis is on doing the same case over again, not on "replicating" the results of one case by doing another case study.)" (Italics original). Similarly, Merriam situates reliability in line with "dependability" or "consistency" of the results obtained from the data: "rather than demanding that outsiders get the same results, a researcher whishes outsiders to concur that, given the data collected, the results make sense—they are consistent and dependable. The question then is not whether findings will be found again but whether the results are consistent with the data collected." (p. 206). Thus, reliability of a case study depends on how well the procedures were documented throughout the study (Yin, p. 36; Merriam, p. 207).

It was the purpose of this chapter to lay out data collection methods and procedures as explicitly as possible. Earlier sections described in detail what data collection methods were used, in what manner, and in which order. It was also the intention of this chapter to
portray how all these different pieces fall in place together (see section 3.1.4, figure 3.3, and table 3.1). In short, I wanted to make sure that the methodology of this study is clearly laid out and portrayed in order to enable interested third parties to make sense of the nature of the data and, if desired, replicate the same methods and procedures in other studies.

Another way to check for reliability of a case study is via researcher triangulation – having more than one researcher present during data gathering and analysis. Although there was not a second researcher per se involved in data gathering in this study (i.e., interviews were conducted solely by me) I teamed with the faculty in designing the course, which started almost a year before the start of data collection, and constantly shared developing insights with them during the preceding semester and throughout the data gathering. I also benefited from valuable feedback while the study was underway: I developed, modified, and added new data collection methods to the study.

Moreover, I prepared preliminary reports focusing on different parts of this study and presented them at professional meetings several times (1999-Summer and 2000-Winter Meetings of American Association of Physics Teachers, 2000 Annual Meeting of the American Educational Research Association, 2000 Annual Meeting of the National Association of Research in Science Teaching). This provided me with valuable feedback from the referees and colleagues from all over the world.

Reliability is an important concern that needs to be taken into account while designing a research program. Table 3.3 lists main concerns about reliability and the researcher's answers as they relate to this study.
Table 3.2. Reliability check.

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Were the data collection methods and instruments documented and described properly?</td>
<td>YES</td>
</tr>
<tr>
<td>Can an independent judge authenticate the findings by following the trail of the researcher?</td>
<td>YES</td>
</tr>
<tr>
<td>Will all such studies yield exactly the same results?</td>
<td>NO</td>
</tr>
<tr>
<td>Was there a researcher triangulation in the strict sense?</td>
<td>NO</td>
</tr>
<tr>
<td>Were the data sources triangulated?</td>
<td>YES</td>
</tr>
<tr>
<td>Were the methods of data collection triangulated?</td>
<td>YES</td>
</tr>
<tr>
<td>Are the results obtained from the data &quot;dependable&quot; and &quot;consistent?&quot;?</td>
<td>YES</td>
</tr>
<tr>
<td>Was the theoretical framework behind this study explained clearly?</td>
<td>YES</td>
</tr>
<tr>
<td>Were the context and the characteristics of this study described adequately?</td>
<td>YES</td>
</tr>
</tbody>
</table>

"Der Apfel fällt nicht weit vom Baum und das Kalb geriet gewönlich nach der Kue."
(The apple does not fall far from the tree, and the calf usually resembles the cow). --German proverb.

3.2.3 External validity: Generalizing the findings

Having already discussed internal validity and reliability issues, the focus now turns to the external validity of case studies: What are case studies worth? What is the nature of the outcomes of a case study and what can be learned from them? Obviously, any discussion on methodological issues will be weak without consideration of these questions. In this subsection answers will be sought first for case studies in general and then for this study in particular. It is appropriate to begin with definitions of a case and case study before going further.

Kolodner (1993) defines a case as "a contextualized piece of knowledge representing an experience that teaches a lesson fundamental to achieving the goals of the reasoner."
Merriam (1998) defines the case study by its special features. According to her qualitative case studies can be characterized as being particularistic, descriptive, and heuristic:

Particularistic means that case studies focus on a particular situation, event, program, or phenomenon. … Descriptive means that the end product of a case study is a rich, "thick" description of the phenomenon under study. … Heuristic means that case studies illuminate the reader's understanding of the phenomenon under study. (pp. 29-30).

Thus, if a case study is by its nature particularistic and contextualized, what can be said about its external validity? That is, to what extent can the findings of one study be extended to and applied in other situations? How generalizable are the results of a research study? (Merriam, 1998, p. 207)

Traditionally, scientific generalizations are determined by inductive methods. "It is usual to call an inference 'inductive' if it passes from singular statements (sometimes also called 'particular' statements), such as accounts of the results of observations or experiments, to universal statements, such as hypotheses or theories [all italics are original]." (Popper, 1959, p.27). The essential point here is concerned with the nature of scientific knowledge, i.e. do universal statements reflect absolute truth or are they somewhat tentative? Figure 3.7 illustrates the point of view that an inference based on valid and reliable observations (or experimental measurements) must coincide with the reality and hold true beyond any doubt.

At the beginning of this section, it was asserted that "science is a means of generating knowledge," an exploration into the unknown. For that reason, reality can never be induced from particulars with complete confidence; such confidence would require a meta-knowledge to assert that the set of experiences does indeed coincide with the reality (or absolute truth). That is, even if a large number of observations are found to be reliable (i.e. coherent, supporting each other) that does not necessarily place (or shift) reality right on that
realm. In his famous book *The Logic of Scientific Discovery*, Sir Karl Popper (1959) rejects inductive verification (pp. 27-30) and defends deductive testing (pp. 32-34). He states that:

> Now in my view there is no such thing as induction. Thus inference to theories, from singular statements which are 'verified by experience'
(whatever that may mean), is logically inadmissible. Theories are, therefore, *never* empirically verifiable. … I shall certainly admit a system as empirical or scientific only if it is capable of being *tested* by experience. These considerations suggest that not the verifiability but the falsifiability of a system is to be taken as a criterion of demarcation. In other words: I shall not require a scientific system that it shall be capable of being singled out, once and for all, in a positive sense; but I shall require that its logical form shall be such that it can be singled out, by means of empirical tests, in a negative sense: *it must be possible for an empirical scientific system to be refuted by experience*. (p. 40)

He goes further and draws the limits of what generalization means; he claims that scientific endeavor can exist as long as there is room for further tests (p. 53), but absolute certainty can never be demonstrated. Thus,

The demand for scientific objectivity makes it inevitable that every scientific statement must remain *tentative for ever*. (p. 280) Science does not rest upon solid bedrock. The bold structure of its theories rises, as it were, above a swamp. It is like a building erected on piles. The piles are driven down from above into the swamp, but not down to any natural or ‘given’ base; and if we stop driving the piles deeper, it is not because we have reached firm ground. We simply stop when we are satisfied that the piles are firm enough to carry the structure, at least for the time being. (p. 111)

On the other hand, case studies are not even repeatable in the classical sense as Merriam (1998) describes:

Because what is studied in education is assumed to be in flux, multifaceted, and highly contextual, because information gathered is a function of who gives it and how skilled the researcher is at getting it, and because the emergent design of a qualitative case study precludes a priori controls, achieving reliability in the traditional sense is not only fanciful but impossible. (p. 206)

How, then can case studies be put to test so that their results can either be falsified or corroborated by further studies (or observations)?

Although other approaches exist (see Merriam 1998, pp. 208-211) one solution to this problem is that, given the nature of the cases, drawing conclusions from a case study for a newly encountered case requires that one know not only what lesson(s) the former teaches
but also the context in which it can teach its lesson(s) (Kolodner, 1993, p.13; Riesbeck, & Schank, 1989, p.25). The emphasis on the contextualized nature of each case needs special attention since it is a very essential feature of cases. It means that cases cannot be categorized on a trivial basis, and generalization without an understanding of the context might often give misleading results. Therefore, when a reader bases his/her reasoning on a specific case (i.e. driving conclusions for a new case by using an existing one) the nature and the details of the problem and the contexts in both cases need to be relevant.

In the same line Lincoln and Guba (1985) argue that outcomes of a case study can be discussed at a level which may most usefully be thought of as the "lessons to be learned" from the study, and that "the reader should carefully note that these lessons are not [emphasis original] generalizations but "working hypotheses" that relate to an understanding of the site [case]" (p. 362). Therefore, from a case study "at best only working hypotheses may be abstracted, the transferability [emphasis original] of which is an empirical matter, depending on the degree of similarity between sending and receiving contexts" (p. 297). This puts the onus on the reader/reasoner of a case study to judge if an inference is applicable in his/her own case (or problem situation):

In order to be sure (within some confidence limits) of one's inference, one will need to know about both sending and receiving contexts. We move then from a question of generalizability to a question of transferability [emphasis original]. Transferability inferences cannot be made by an investigator who knows only [emphasis original] the sending context (Lincoln and Guba, 1985, p. 297).

Similar thoughts have been expressed by Merriam (1998, p. 211, and the references there), Taber (2000), Steffe and Thompson (2000, p. 304), and Cobb (2000, p. 327) as well.

This is, of course, a different way of conceptualizing the generalizability issue. However, it seems to be the most viable one for case studies. When findings are summarized
into a hypothesis, model, or theory, a case study can become a vehicle for examining other cases (Yin, 1994, p. 37). Taber (2000) suggests that case study findings should also be "tested" by "replication studies with other samples of learners," particularly in diverse settings such as different types of institutions or education systems. If working hypotheses driven from one case study survive the scrutiny of other researchers and various tests, then they have received corroboration.

Researchers choose to carry out a case study because they are interested in insight, discovery, and interpretation rather than hypothesis testing: "By concentrating on a single phenomenon or entity (the case), the researcher aims to uncover the interaction of significant factors characteristic of the phenomenon" (Merriam, p. 29). This is particularly relevant when the boundaries between the context and the phenomenon are not clearly evident (Yin, 1994, p. 13). Therefore, it is only possible to reject the findings of a case study by means of logical analysis which shows that the study is not internally valid and/or reliable. Table 3.3 lists several concerns related to external validity and the researcher's answers as they pertain to this study.
Table 3.3. Generalizability check

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>By their nature should the potential findings of this study be confined strictly to this case of learning only?</td>
<td>NO</td>
</tr>
<tr>
<td>By its nature can this study potentially provide insights of wider value, i.e. is it relevant to wider contexts?</td>
<td>YES</td>
</tr>
<tr>
<td>By their nature are the potential results of this study readily generalizable to all individual cases of learning?</td>
<td>NO</td>
</tr>
<tr>
<td>By its nature can this study be replicated elsewhere in different institutions and/or in different education systems?</td>
<td>YES</td>
</tr>
<tr>
<td>By their nature are -at least certain aspects of- potential findings of this study open to statistical testing and generalization?</td>
<td>YES</td>
</tr>
<tr>
<td>Was a rich and vivid description of participants provided?</td>
<td>YES</td>
</tr>
<tr>
<td>Was a rich and vivid description of the context of the study provided?</td>
<td>YES</td>
</tr>
<tr>
<td>Was a rich and vivid description of the nature of interaction between the participants and the researcher, and between the participants and the instruments provided?</td>
<td>YES</td>
</tr>
</tbody>
</table>
Ah! my dear Watson, there we come into those realms of conjecture, where the logical mind may be at fault. Each may form his own hypothesis upon the present evidence, and yours is as likely to be correct as mine.


4.1 Introduction

This chapter is dedicated to portraying June's (a pseudonym) alternative framework and learning about force and motion. The data come from several sources: transcripts of video recordings of three two hour classroom sessions, audio recordings of two one-on-one interviews each approximately one and a half hours and three shorter follow-up interviews, paper-pencil tasks (i.e. pre-test/post-test, and a word association task), and documents (i.e. June's journal entry and notes taken during interviews).

Data collection started during a short unit on simple machines in which June participated as a student and the researcher acted as the instructor (see section 3.1.2.1 and 3.1.2.3). On the first day of the Simple Machines unit, the students in the case study group took a pre-test and provided extended answers to the questions. The first three sessions of
the unit were spent discussing force and motion, and the rest of the unit was spent on simple 
machines. The students also responded to another conceptual test on the eighth class 
meeting day. During instruction, further data were collected by means of student journal 
entries, verbatim transcripts of tutoring interviews, and a word association task. In first two 
tutoring interviews, conducted during the instructional period, June appeared to develop 
more scientific ideas about these concepts.

In order to probe June's ideas about the same concepts in a delayed period, I 
interviewed her again exactly one year after the first interview. She was interviewed in two 
subsequent sessions which included both think aloud and paper and pencil tasks. Thus, the 
data collection period spanned approximately a 14-month period from beginning to end. 
Table 4.1 gives the chronology of instruction and data collection.

To demonstrate June's conceptual understandings and difficulties in a 
comprehensive way, the data will be introduced chronologically followed by descriptions and 
interpretations in the later sections. Rather than presenting the data in the form of coded 
themes, I chose a chronological presentation with cross-references and feedbacks which 
makes it possible to reveal both the individual conceptions and the relationships between 
them without fragmenting the meaning.

During the group instruction and tutoring interviews, I introduced cognitive 
challenges to June (demonstrations, experiments, and examples of everyday experiences 
involving force and motion). Cognitive challenges involve discrepant events, which can 
create cognitive dissonance. Hence, June's alternative framework and learning have been 
probed and investigated during the period of the study.
The pre-test revealed that June's initial understandings were not scientifically accurate (see section 4.2.1). Through classroom discussions I became aware that the nature of conceptual understanding regarding force and motion was much more complicated for the students than he originally thought. Thus, inquiring more about June's reasoning and learning about acceleration in relation to force and speed in different contexts (i.e. daily push-pull experiences, motion on frictionless surfaces, and free fall) led to a very interesting sequence of conversations with June during one-on-one tutoring interviews.

I first wanted to delineate June's ways of dealing with concepts related to force and motion. June was almost always able to give accurate definitions of force, velocity, and acceleration as they were discussed in class, but a particular conceptual difficulty surfaced when she was asked to use those definitions in various situations: relating acceleration to force and velocity/speed. I took a qualitative approach with an emphasis on conceptual understanding in my discussions with June without using any of the kinematics formulas relating acceleration \( \dot{a} \) to speed \( \dot{s} \). For example, we and discussed qualitatively the definition of acceleration as "the rate of change of velocity," but we never gave or discussed the formula for average acceleration \( \bar{a} = \Delta \dot{s} / \Delta t \) or went on to calculating acceleration and velocity using these formulas. On the other hand, we often discussed and used Newton's second law \( F = ma \) relating force directly to acceleration.

During the tutoring interviews, my intent was first to help June verbalize her current understandings by asking open ended questions and then, by posing challenges (discrepant events contrary to her intuition), to make her re-think problem situations differently in order to foster a more scientific understanding. Nevertheless, it was not the purpose to teach her how to solve kinematics problems by using formula-based strategies. At times during the
interviews, I provided June conceptual explanations and guidance in her thinking by asking challenging questions.
Table 4.1. Chronology of instruction and data collection.

<table>
<thead>
<tr>
<th>Week of Instruction</th>
<th>Day of Instruction</th>
<th>Date of Activity</th>
<th>Instructional Activity</th>
<th>Data Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 1</td>
<td>Day 1</td>
<td>Feb 16, 1999</td>
<td>Discussion on pretest questions, Vectors (and scalars), Concept of Force.</td>
<td>Pre-test (§ 4.2.1) Video Recording (§ 4.2.2.1)</td>
</tr>
<tr>
<td></td>
<td>Day 2</td>
<td>Feb 18, 1999</td>
<td>Concept of Force, Inclined Plane, Weight, Friction</td>
<td>Video Recording (§ 4.2.2.2)</td>
</tr>
<tr>
<td>Week 2</td>
<td>Day 3</td>
<td>Feb 23, 1999</td>
<td>Concept of Force, Inclined Plane, Acceleration &amp; Velocity, Friction</td>
<td>Video Recording (§ 4.2.2.3) Journal (§ 4.2.3)</td>
</tr>
<tr>
<td></td>
<td>Day 4</td>
<td>Feb 25, 1999</td>
<td>Simple Machines</td>
<td></td>
</tr>
<tr>
<td>Week 3</td>
<td>Day 5</td>
<td>Mar 2, 1999</td>
<td>Simple Machines</td>
<td>Tutoring Interview - I (§ 4.2.4)</td>
</tr>
<tr>
<td></td>
<td>Day 6</td>
<td>Mar 4, 1999</td>
<td>Simple Machines</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mar 8-12, 1999</td>
<td>Spring Break</td>
<td></td>
</tr>
<tr>
<td>Week 4</td>
<td>Day 7</td>
<td>Mar 16, 1999</td>
<td>Simple Machines</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Day 8</td>
<td>Mar 18, 1999</td>
<td>Simple Machines</td>
<td>Post-test (§ 4.2.5), Group Embedded Figures Test</td>
</tr>
<tr>
<td>Week 5</td>
<td>Day 9</td>
<td>Mar 23, 1999</td>
<td>Simple Machines</td>
<td>Tutoring Interview - II (§ 4.2.6)</td>
</tr>
<tr>
<td></td>
<td>Day 10</td>
<td>Mar 25, 1999</td>
<td>Simple Machines</td>
<td></td>
</tr>
<tr>
<td>Week 6</td>
<td>Day 11</td>
<td>Mar 30, 1999</td>
<td>Design Project</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Day 12</td>
<td>Apr 1, 1999</td>
<td>Field Trip to College of Engineering Open House</td>
<td></td>
</tr>
<tr>
<td>Week 7</td>
<td>Day 13</td>
<td>Apr 6, 1999</td>
<td>Design Project</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Day 14</td>
<td>Apr 8, 1999</td>
<td>Design Project</td>
<td></td>
</tr>
<tr>
<td>Week 8</td>
<td>Day 15</td>
<td>Apr 13, 1999</td>
<td>Design Project Group Presentations</td>
<td>Word Association Task (§ 4.2.7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Apr 15, 1999</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long after instruction</td>
<td></td>
<td>Mar 3, 2000</td>
<td>Tutoring Interview - III (§ 4.3.1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mar 31, 2000</td>
<td>Force and Motion Conceptual Evaluation (FMCE) (§ 4.3.2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Apr 12, 2000</td>
<td>FMCE Follow-up (§ 4.3.3)</td>
<td></td>
</tr>
</tbody>
</table>
4.2 Understanding June's Conceptions During Spring 1999

At the start of the Simple Machines unit the students in the case study research group were given a pretest which included basic concepts of force and motion (see Figure 4.1). Section 4.2.1 provides my interpretation of June's preconceptions revealed through this pre-test. Section 4.2.2 describes the nature of the instruction and gives examples of conversational exchanges with the participating students. Since the purpose of this chapter is to describe June's alternative framework and learning on force and motion the excerpts from video recordings of the classroom sessions with the case study group provide a valuable source of data. Descriptions of the classroom sessions lay out the context in which June's and other student's initial ideas were challenged. This section also provides a foundation for the rest of the chapter since some of June's learning about force and motion took place during this time period.

4.2.1 Pre-test

In order to probe the students' understanding of force, acceleration, and velocity, I included six questions in the conceptual pre-test. These questions were intended to elicit the students' reasoning about these concepts qualitatively. Considering their very limited background in learning physics, this type of question was deemed appropriate and informative. The questions and June's responses are presented in Figure 4.1. All italics are hers, and she did not provide any drawings. She made no statement about the absence or presence of friction in these questions. In her answer to the fifth question she inserted the word 'more' as an addition after she wrote the sentence.
2.16.1999

1. What is a vector? Please describe and give examples of vector quantities.
   
   A vector is a component force designated by arrows.

2. What is a force? Please describe and give examples of types of forces you can remember at this moment.
   
   A force is a push or pull that affects an object. There are compressive forces which push in on an object and tensile forces which pull out on an object. Gravity is a force that pulls objects to the earth.

3. If a body is speeding up, what can you say about the force(s), if any, acting on it? (Draw a diagram if you like.)
   
   If a body is speeding up then it either means that there are excessive forces causing it to speed up or that there is an absence of forces like friction, which would slow the body down.

4. If a body is moving with constant speed, what can you say about the force(s), if any, acting on it? (Draw a diagram if you like.)
   
   A body moving at constant speed is being acted on by forces in equilibrium.

5. If a body is slowing down, what can you say about the force(s), if any, acting on it? (Draw a diagram if you like.)
   
   If a body is slowing down then there are either forces pulling on it to stop like friction or there are no forces which caused the initial movement.

6. If a body is at rest, what can you say about the force(s), if any, acting on it? (Draw a diagram if you like.)
   
   A body at rest is in equilibrium. The forces are equal and opposite.

Figure 4.1. June's responses to pre-test questions on force, acceleration, and velocity.

From June's answers to questions 1, 4, and 6 –designating a vector as "a component force" and using the term "equilibrium"– it is evident that she is trying to incorporate what she had learned in the first unit of the course ('Structures and Stability'). Her explanations in for questions 3 and 5 are vague and do not reveal precisely what she means. In both answers
she refers to friction as a force that opposes motion. That is correct. However, the presence of friction does not cause an automatic slow down. Since friction is always in the direction opposite to motion, it produces a slowing effect for a moving object if it is greater than the force (if any) in the direction of the motion. June does not link the cause of slowing to friction if an object is pushed and let go. It is understood that she wants to say it is harder to move an object if friction exists. Hence, the less the friction, the easier to move on a surface. It can be concluded that her understandings of such situations are more intuitive than conceptual.

Her understanding of "speeding up" is revealed in two ways: by the presence of excessive forces in the direction of motion, or by the absence of friction. She says that excessive forces increase speed while friction decreases. Both of these statements are partially true in the Newtonian sense: any net force causes acceleration proportional to its magnitude on an object. In the presence of friction, on the other hand, more force is required to attain the same net force and acceleration since it opposes motion. She might just be trying to state that the difficulty of moving an object increases as the friction increases.

For the case of an object 'slowing down,' June responds in a very peculiar way. She gives two statements to explain how an object might slow down. First, she indicates that an opposing force is required for an object to slow down. But she also states that a body would slow down if "there are no more forces which caused the initial movement," possibly meaning that in order to keep an object in uniform motion, an applied force is needed constantly times. Thus, when an object is let go, its speed will decrease at all subsequent
times, eventually coming to a stop; this is the case in real life situations where friction cannot be totally eliminated. This conception is reminiscent of the impetus theory.

June characterized both 'constant speed' and 'at rest' situations with the same descriptor: "equilibrium." Newton's first law states that:

\[
\text{every material object continues in its state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it} \quad (\text{Hewitt, Suchocki, \\& Hewitt, 1999, p. 31}).
\]

Therefore, although "constant speed" or "at rest" implies no net force in any direction, as June suggested, previous history of motion is the major determinant of the motion under such circumstances. Zero net force might be attained either by equal and opposing forces acting on an object or by absence of forces in all direction. That is, if no forces are acting on an object in motion with constant speed, then it shall maintain its velocity unless its state of motion is disturbed by a force, a case overlooked by June.

### 4.2.2 Three Days of Instruction on Force and Motion

At the beginning of simple machines unit a brief introduction was held on force and motion. During the first three classroom sessions students' preconceptions were explored through discussions and demonstrations. Students freely expressed their views and interacted with each other and me to arrive at conclusions. In the following three subsections an account of what happened during these classroom meeting times is given, with particular attention paid to critical incidents.
4.2.2.1 Day 1: Vectors and Introduction to Newton's Third Law of Motion

The first session was held on Tuesday, February 16, 1999 between 9:00 and 11:00 AM. The classroom session was video recorded as all sessions were. This was the first separate meeting of the small group from the main class. The first half of the session was spent on responding to the pre-test questions individually (not recorded.) Below is an account of the second half of the session compiled from video recording.

Students sat in a row facing the white board and me; the camera was located several feet behind them. The second half of the session started with the instructor's brief introduction to the simple machines unit. The purpose of the unit was described as learning about simple machines and incorporating that knowledge to help design a lift bridge. The rest of the hour was dedicated to discussing scalar and vector quantities, vector algebra, and Newton's third law. During the discussions students had many opportunities to express their thinking and reasoning so a highly interactive, studio format of teaching could be adopted. For each concept the students first communicated what they knew about it and then responded to each other's ideas and my challenges.

For example, June and Mae stated that mass and weight were two different names for the same thing. Then the group proceeded to arrive at a definition for both mass and weight and examined how the characteristics of vectors and scalars (the differences) applied to them. This way of teaching was deemed useful in fostering a minds-on learning environment, where the students actively interacted with each other, the instructor and the material being taught.
The session continued with a discussion of the definition of force and the conceptualization of it as a vector. The students agreed on its definition as a "push or pull." The group then discussed separating an arbitrary force into its components in two dimensional Cartesian coordinates. The parallelogram method was introduced for addition of two or more forces in arbitrary directions. Also, a computer program, available on the World Wide Web (at the Virginia Tech University's Java Applets for Engineering Education site: http://www.engapplets.vt.edu/), was used to demonstrate examples of vector addition by this method and the students were advised to use this online software to gain practice with the method.

The session concluded with two introductory activities about Newton's third law of motion: Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first (Hewitt, Suchocki, & Hewitt, 1999, p.43.) The first activity was determining what effect pulling down on a rope hanging from the ceiling would have on one's weight. It was somewhat surprising and amusing for the students to see that they weighed less when they stood on a bathroom scale and pulled down on a rope firmly attached to the ceiling. Mike explained the situation as "some of my weight goes up," and June stated it happened "because this [rope] is supporting some of my weight." The second activity was pushing a wall while sitting on a rolling chair. The students' were asked to compare this case to pushing the wall while standing up. All students did these activities and as an assignment for Thursday they were asked to think of an explanation to what they experienced in these two activities.
4.2.2.2 Day 2: Newton's Third Law of Motion, Inclined Plane, Weight, and Friction

The second session of small group classroom instruction was held on Thursday, February 18, 1999 for two hours between usual class times. Below is an account of the session compiled from video recording.

The session started with a discussion of the two activities conducted at the end of the previous session. The students provided what they thought as possible explanations:

Mae: I would have thought the weight would go up. But you are not really changing anything, you are just pulling the string. Then more of your weight is going to the string.
June: We said weight was gravity acting on mass so if you're pulling downward then I don't think gravity is … I don't know …
Mike: My theory is when standing on the bathroom scale you are not doing anything all the weight is going downward, it is all going to the scale. But when you're pulling up on the string you are actually giving to the string some of your weight. Because you are pulling up on it and it is taking some of your weight causing not all your weight to go towards the scale.
April: When you hold on to the string it is because there is not as much of you on the scale.

After gathering the students' initial thoughts, I introduce some challenging questions, encouraging them to think in terms of the forces involved and to identify those forces. Discussion goes to friction forces, action-reaction pairs of forces, and forces as causing either initiation of motion or a change in motion.

I give the following example:

Instructor: Now, I push and release this toy car on a horizontal table top. It went about like three feet and then stopped. Why?
Mae: If you continued pushing, then it'd continue to move.
Mike: The amount of force you put on it, the amount of force you pushed on it is distributed between the wheels causing the wheels to keep going till you know eventually using up all of the force put up on it.
Instructor: So, the wheels use up the force?
Mike: Yeah.
Instructor: Okay. [points to June] Do you wanna say anything?
June: I agree!
Instructor: April, do you wanna say anything? Do you also agree?
April: Yeah.
In the second half of the session the group discusses the definition and effects of friction on motion by using an inclined plane (a table which can be turned into an inclined plane by raising one side of the table top.) Examples are given from daily life, such as riding a bicycle (even if one does not pedal, the bike speeds up continuously), or pushing a load in a cart up a ramp. We then discussed finding the components of weight in the directions parallel and perpendicular to the surface of an incline. The effect of the slope of a ramp on the magnitude of the weight component in the direction parallel to the surface was demonstrated, indicating that at the extreme case of 90 degrees the motion would resemble a free fall.

The session was closed by concluding that one needs to lift the whole weight of a load to raise it straight up, while pushing the same load on a ramp simply requires overcoming friction plus the parallel component of the weight of the load to the surface of the ramp:

Mike: Lifting straight up you'll lift whole, entire, 100% of the weight. But, the person pushing on the slope is gonna have an easier time because they have some of the percentage of the weight perpendicular to the surface of the slope and some percentage parallel to the surface. Wheels of the cart help reduce the friction.

4.2.2.3 Day 3: A Net Constant Force and Summary of Force and Motion

On Tuesday February 23, 1999, the last session on force and motion was held at regular class meeting times. Below is an account of the session compiled from video the recordings.
The students sat in two groups facing each other, June and Mae are in one group, April and Mike in the other. The white board is on the third side of the table, and the camera is located opposite it. A table, which can be turned into an inclined plane by raising one side of its top, was placed between the groups' desks so that all could easily see the demonstrations.

The session begins by reviewing the central concepts covered thus far. A discussion starts on friction, forces, and conditions for staying at rest in the presence of forces and initiating motion. Then the case of inclined plane is discussed: Why and how an object can stay at rest on an inclined plane, how the slope effects the forces on an object placed on a ramp, and how this case compares to staying at rest on a horizontal surface. So far the students look quiet relative to the previous two sessions. By asking questions, I continuously encourage them to participate in the discussions and voice their ideas.

My task is to summarize all that was done and said in terms of rules. The first rule they agree on is that forces exist in pairs (Newton's third law): whenever two objects interact, every force applied on the first by the second is associated with a reaction force it which counteracts on the second, and these forces are equal in magnitude and opposite in direction.

By considering the case of an object staying at rest on an inclined plane, the second rule is formulated, after several re-formulations by the students, as at-rest condition: "if the resultant force of all the forces acting on an object is zero then the object will stay at rest." An extension of this becomes rule #3: "If the resultant force of all forces on an object is greater than zero it will begin motion in the direction of the resultant force." This rule was exemplified again by the case of the inclined plane (when the slope is increased slowly a
point is reached where downward pull parallel to the surface overcomes friction which initiates motion), and by biking downhill.

I illustrate the latter using a toy car released from the top of inclined plane. April states that the job of wheels is to reduce friction. In order to further engage the students, I show the meter imprint on the table top and, by pointing to 10cm intervals, ask what they expect to happen to the speed of the toy car in each subsequent equal interval while it travels down the inclined plane. I then release the toy car a couple times as an example, and June suggests that the speed will increase. They all agree that this is similar to biking downhill.

Up to this point, the students were quieter than in the previous week's sessions. But now this gets them more engaged, and they begin constantly asking various questions. The students' questioning this way also allows voicing their ideas out loud.

At this time a crucial point is reached when I introduce this question: "Why is that? [why the toy car speeds up?] Slope is the same all over the tabletop. Is there a constant net force on the toy car throughout its motion on the inclined plane?" They all respond by saying "yes!" I now ask the students to formulate this case as a rule. One by one, the students attempt formulating a rule, as they understand the situation:

June: If there is a resultant force on an object, then the speed doesn't change.
FT*: Is it the case? [demonstrates with the toy car couple more times]
April: Speed increases.
Mike: [jumps in] I am really confused!

June first gives a statement of her version of the rule, and the other students share her idea. June is explaining that a constant force produces a constant speed. Though I had tried to demonstrate this principle using an inclined plane and a toy car, it

* In all transcriptions I will refer to myself by my initials (FT).
had not yet been expressed verbally. Naturally, students begin voicing their genuine ideas first. April notices that during the demonstration the toy car gains speed as it moves down the inclined plane. When this demonstration is verbalized, it creates confusion as Mike expresses that something must be wrong!

FT: Does the component of weight parallel to the surface of the incline stay constant at all points on the surface of the incline?
Mike: Oh, I see. Yeah!
FT: So, that means neither the magnitude nor the direction of the net force on the object changes. Therefore, there is a constant net force on the object, which makes the speed to increase.
[Mae shakes her head to indicate that she agrees]
Mike: The speed increases because there is not .. [leaves unfinished]
FT: .. there is not? What is your idea?
Mike: .. I don't know ..
April: If the net force on it is constant why does it speed up? I mean I can see that it does, but .. I don’t .. [leaves unfinished]
Mike: The net force is equal along the whole way.
FT: So what do you think? If the force is constant it should have a constant speed? Is that your original idea?
April: I don't know ..
Mike: I think it has something to do with just .. [leaves unfinished]
June: Does it have something to do with like the weight that was behind it, like a big brake going downhill got off brake and just let it go. Do you know what I mean?
FT: It goes just by ..
Professor: That's illegal by the way.
[all laugh together]
June: You have to get out of their way. I mean there is .. they have so much weight behind it. I don't know if that has anything to do with it.

I once more repeat the demonstrations on the inclined plane and the explanations on the white-board and ask:

Instructor: What did you think the speed would be, if there is a net force?

June responds that while biking downhill she thought "force behind us was getting stronger, that would have explained speeding up," and she adds, "I now realize that the force is not gonna change unless the slope doesn't change." To conclude the discussion on constant force, a third rule is formulated:

April: How about 'a net constant force makes an object speed up.'
The session concludes with a discussion of the definitions of speed, velocity, and acceleration. Additionally, the meaning of position as a vector is discussed with examples from daily life such as giving directions to someone with respect to a reference point (e.g. five blocks to the West on Main St. from the corner of Church St.) This way a position contains both magnitude (distance) and direction as all vectors should.

From these data it is evident that the students' preconceptions of force and motion were quite similar. The essential point is that they all associated increasing speed with increasing force on an object. This idea can be formulated as 'the more the force, the more the speed' or $F \propto s$. That is, in order to increase the speed of an object, it needs to be pulled or pushed in the direction of motion with a greater amount of force. This statement would also indicate that a slow down is caused by a lessening of force on an object. Additionally, according to the students, attaining a constant speed requires pushing or pulling an object by a force constant in strength. These results are summarized in Table 4.2.
Table 4.2. Students' conceptions of Newton's Laws.

<table>
<thead>
<tr>
<th></th>
<th>Students' Laws of Motion</th>
<th>Newton's Laws of Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Law</strong></td>
<td><em>No motion without force and no force without motion.</em> Force implies motion and motion implies force.</td>
<td>Every material object continues in its state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it (p. 31)</td>
</tr>
<tr>
<td><strong>Second Law</strong></td>
<td><em>The more the force, the more the speed.</em> The speed of an object is directly proportional to the amount of force acting on the object, and the object moves in the direction of the force.</td>
<td>The acceleration of an object is directly proportional to the net force acting on the object, is in the direction of the net force, and is inversely proportional to the mass of the object (p. 36)</td>
</tr>
<tr>
<td><strong>Third Law</strong></td>
<td><em>Non-interactive model.</em> Forces exist in isolation. It is simply that one agent exerts force on an object.</td>
<td>Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first (p. 43)</td>
</tr>
</tbody>
</table>
4.2.3 June's Journal Entry on Force and Motion

The students' were encouraged to keep a journal throughout the unit. June's journal written after the third day of instruction is presented in figure 4.2.

The main points I took from Tuesday were:

**FORCE:**

1. is a push or pull
2. is a vector quantity, \( \vec{F} \) has direction and magnitude.
3. ALWAYS has action-reaction pair which must be equal in magnitude and opposite in direction.
4. If the resultant force (of all acting forces) on an object is ZERO, it won't move.
5. If the resultant force (of all acting forces) is greater than ZERO, it will move in the direction of the resultant force.
6. A net constant force makes an object **Speed** up!!!
   - speed is magnitude of velocity without direction
   - velocity gives the direction \& magnitude of the rate of change of position
   - acceleration = rate of change of velocity
   - \( F = am \)

\( F \) is proportional to \( a \) and to \( m \). I think I understand most of this. I need to review it a few more times to get the terminology correct.

Figure 4.2. June's journal entry, which summarizes her understandings of the sessions about force and motion.

The items in June's journal can be characterized as follows: items 1 & 2 are descriptive, item 3 states Newton's third law, items 4 & 5 state Newton's first law (for an object already at rest), item 6 states Newton's second law as discussed in class (see section 4.2.2.3). Here June merely repeated the rules made with the students in class. Noteworthy
points include: item 6, in which June underlined the word "speed" and used three exclamation marks at the end of the sentence, perhaps indicating that she put a lot of emphasis on this statement, a normal reaction considering she wrote this journal after the third day of instruction (see section 4.2.2.3), and that the students, including June, had a great deal of difficulty associating constant force with increasing speed. Another significant thing in this artifact is that June gave accurate definitions of the three concepts, namely velocity, acceleration and force. This piece also reflects the terms in which Newton's three laws were discussed in class (without referring to them as Newton's laws), and how June noted them. She clearly indicated that acceleration is the rate of change of velocity, and that force equals mass times acceleration and is proportional to both of them. However, it cannot be inferred from this artifact what exactly she understands from all these statements. The tutoring interviews with June (see sections 4.1.4 and 4.1.6) give more detail of her understandings and reflect her conceptual difficulties.

4.2.4 Tutoring interview – I : Culminating classroom discussions

On March 3, 1999 I conducted the first interview with June in the third week of the Simple Machines unit after three days of instruction on force and motion concepts and two days of instruction on simple machines (see table 4.1). This interview session lasted about 90 minutes.

The dialogue began with a discussion of June's background in learning physical science and related school subjects, her learning in the 'Fundamentals of Science and Engineering Design' course, and the nature of this course. Additionally, June's ideas on
several concepts (i.e. pulley, friction, vector, and work) were briefly discussed. This initial
dialogue, in addition to obtaining such information, also warmed her up for the more
essential parts of the interview to follow by establishing a basis for "easy-talk" and a natural,
conversational attitude rather than an authoritative questioning.

4.2.4.1 Acceleration: "the rate of what you speed up"

We soon begin discussing acceleration, and I start by asking June questions of how
she defines acceleration. June responds:

| June: | Umm.. [pause] probably the rate of what you speed up. I but [pause] |
| FT:   | Umm, so if you are not speeding up? |
| June: | You're decelerating. |
| FT:   | You mean if you are slowing down? |
| June: | If you are slowing down, yeah. |
| FT:   | Okay.. Okay and what if your speed is constant? |
| June: | [pause] uhh |
| FT:   | If you apply the definition to this case.. you are like making something to travel with
      | some certain speed and the speed doesn't change along the way.. |
| June: | [pause] So, is that a constant rate of acceleration? Is that what you are saying? |
| FT:   | I don't know. You are going to tell me [jokingly]. |
| June: | [chuckles, no response] |

Upon my request for further elaboration June responds:

| June: | Well, I don't really know what it is, but I would say that it was I think I said the
      | rate with which you speed up. |

(Interview Excerpt 1.1, March 3, 1999, lines 209-226)

Apparently, June is confused with the concept of acceleration. She can give the
definition but cannot apply it successfully to different situations. Her first alternative
conception about understanding force and motion, namely 'the more the force the more the
velocity' conception, was detected earlier in her pre-test response and classroom discussions.

Now I am confronted with a second type of difficulty, a naïve interpretation of acceleration: In her
terms acceleration is merely an indicator of whether or not an object speeds up. Therefore, constant speed corresponds to constant acceleration.

4.2.4.2 Rate of change

I decide to probe in more detail about what "rate of change" means to June, not being so sure that June understands this concept even though she uses that terminology to define acceleration. We continue talking about velocity as "the rate of change of position," and this part of the discussion shows that my hunch was correct: June indeed needs the rate of change concept clarified. After a short discussion June shows hints of a correct understanding:

June: Okay. So, then velocity gives you how fast your position is changing in the north direction.
FT: Yes.
June: Okay and acceleration gives you the rate of change of velocity.
FT: mm hmm.
June: So that's the rate of change of what your position is changing?
FT: Umm.. We can say acceleration is the speed of velocity. How fast your velocity is changing.
June: Okay, Okay. [pause]

(Interview Excerpt 1.2, March 3, 1999, lines 265-273)

Right after June pauses briefly FT asks her a crucial question:

FT: Therefore, if your velocity is not changing your acceleration is ..?
June: [jumps in] Constant.

This response means that June associates non-zero acceleration with a change in velocity. Therefore, if velocity is constant (not changing) so is acceleration. June's answer shows that her "understanding" is not so quick and getting rid of old habits of mind is a real challenge for her. In the remainder of this part of the conversation June struggles to decipher what "rate" corresponds to:
June treats "rate" as velocity or "pace." Hence, acceleration is analogous to increasing or decreasing rate (velocity). For a constant velocity she now takes acceleration out of the picture since I said that it would be zero.

4.2.4.3 Constant speed

Defining velocity and acceleration as "rate of change of position" and "rate of change of velocity" respectively, and using concrete examples help June to finally conclude what acceleration would be in a constant speed situation:

FT: So, we define acceleration as the rate of change of velocity and if your velocity is not changing what will be the acceleration?
June: Zero.
FT: Zero right. Just like if your position is not changing your velocity is zero.
June: Correct.

4.2.4.4 Bigger mass falls faster

Now, I decide to explore June's ideas about force and motion in different a context: free fall. When contemplating two objects of different masses dropped from the same height, June's initial idea is:

June: I think the bigger one will hit [the ground] first.
She shows no clear understanding of why and how the amount of mass can make a difference in free fall. Upon renewal of what she says, she responds:

**FT:** So, you are expecting the bigger one to hit the floor first.

**June:** Well, I don’t. I could remember something about 9 point 8 meters per second something.. [inaudible] but I don’t remember what .. what you multiply by that. So, I don’t know if the weight is a factor of it or it is just the level that it is ..

She admits that she remembers this figure from her seventh grade physical science class, but it is "very, very distant"; she is not just guessing. Although she is not sure if she is using the right terminology, her reasoning behind what she thinks would happen rests on an observation:

**FT:** Okay, um so what leads you to think that the bigger mass will hit the ground first?

**June:** Well.. [pause] I was just thinking that because it is heavier it would gather more [pause] speed as it was .. I don't know whether do you speed or acceleration there, um [pause] but if it's [pause] I don't know.

**FT:** But you just feel like it will hit the ground first huh?

**June:** Umm [pause] yeah. Because I am thinking of like a feather and I am thinking of like an anvil and dropping them from the same height the feather is gonna just sort of float down and the anvil is gonna go straight down.. because.. I remember seeing them in toons the cartoons.

**FT:** Yeah.

**June:** Um, because they always drop them on cartoon characters' heads they like throw them out of buildings onto cartoon characters but, um, I don’t know.

**FT:** Does it go faster in the cartoons?

**June:** It does. I mean it is very heavy and it just [pause] it seems to just [makes a sound] flooh.

*(Interview Excerpt 1.5, March 3, 1999, lines 310-345)*

4.2.4.5 Not the mass but the distance traveled during free fall

I prepare a simple experiment at this point: dropping two objects of different masses, one 200 g and the other 10 g, from the same height. He uses a tabletop as the platform. June kneels down and watches closely to see if the objects reach the floor at the
same time. As a result of the experiment she cannot detect a difference in arrival time, which leads her to revise her theory:

**FT:** Was that a surprise?

**June:** No, because I was unsure of what to say but um the more.. the more that thinking about it like it's.. it's the distance that matters, isn't it? Like the height from which you drop it. Because it is gaining the 9 point 8 meters per second [pause] the longer it is dropping the more chance of.. [pause] the more chance it has to.. [pause].

*(Interview Excerpt 1.6, March 3, 1999, lines 357-363)*

June is still not considering the possibility that two different masses can travel at the same pace during free fall. Instead she suggests that if the traveled distance gets longer, the bigger mass will gain speed. This suggestion in a way indicates that she thinks that the heavier object falls faster but it was not possible to detect it in this small experiment.

Here June comes to a point where she has to think more comprehensively. She identified a *cause* for "gathering more speed" as simply "being heavier" during free fall. However, now she adds another cause: "it is the distance that matters." June also uses the expression "9 point 8 meters per second" which she remembers from seventh grade science class, but she is not exactly clear what that means. It seems that June is having difficulty relating concepts to one another. She remembers and makes inferences about many concepts and observations, but they are not connected conceptually.

4.2.4.6 Constant force, constant acceleration, and increasing speed

June then makes observations of a 10 g mass in free fall by at different heights, and she sees that as the height increases, its speed increases more and more towards the bottom. June correctly concludes that:
June: It had more time to pick up speed.

All these observations and reflections prompt June to consider her more recent experiences (classroom sessions on simple machines) on this issue.

FT: So, it speeded up?
June: Yeah. Does this have anything to do with the lever, you know like, with the incline and the net force are... are the... the constant net force caused an actual increase in... in the rate that the object moved down the incline.
FT: So, do you think there is a constant force on it?
June: Yeah, that's gravity [with a sure voice]. That's the 9 point 8 meters per second, isn't it?
FT: It is actually per second square..
June: [jumps in quickly] Per second square.
FT: ... because it is acceleration.
June: Ac-cel-er-a-tion [slowly and clearly enunciating each syllable in an excited manner]. Ta taa! The work of it! [chuckles happily]

(Interview Excerpt 1.7, March 3, 1999, lines 368-379)

This last part of the conversation indicates that June is now starting to make some connections between gravity, force, and acceleration. It also shows that she regards gravity as a constant force on all objects. She had already defined gravity as "a force that pulls objects to earth" (see June's answer to pre-test question 2 in Figure 4.1 where she defined and gave examples of forces). Despite what she revealed earlier as her alternative conception during instruction in day 3 (see section 4.2.2.3), June now states that a constant net force makes objects speed up and gravity is an example of that.

4.2.4.7 Different mass, different force, same acceleration during free fall

Having discussed the roles of the mass of an object and the distance an object travels during free fall in terms of acceleration, I now sum things up by emphasizing that no matter what the mass of an object might be, the pull of the earth (defined as gravity) will give the same acceleration to it. Also, the consequence of having the same acceleration is the same
rate of increase in speed. Therefore, if two objects of different masses are released from the same height, they should end up at the bottom at the same instant. June carefully follows all these explanations and seems to comprehend what acceleration is and understand the relationships between acceleration, height, and mass. However, everything is not over just yet! I remind June of the formula \( F = ma \) (Newton's second law of motion), and we discuss it to see how she will use it in relating the three quantities it includes (i.e. force, mass, and acceleration) conceptually.

FT: Okay. So, How about the forces on these? What did we say about the acceleration of these two masses? [Points to the 10 g and 200 g that they used while experimenting about free fall]

June: That, it is gonna be the same.

FT: It is gonna be the same. [confirms]

June: But the masses are different.

FT: So, forces are [short pause] different?

June: Different. [confirms]

(Interview Excerpt 1.8, March 3, 1999, lines 397-405)

During the class session June expressed her thought that while speeding up the force behind an object gets stronger and heavy objects have greater force behind them due to gravity. Here June agrees, on the contrary, that although the masses of the two objects are significantly different gravity gives them the same acceleration. When the interviewer asks how comfortable she is with this idea, June continues:

4.2.4.8 Not really! If acceleration is the same how can force be different

June: initially I was thinking that .. that 200 g was gonna be.. it was gonna be forcing down more. So, I thought that that would like compliment the speed it would go faster, but that's not the case. It is.. it's constant.

FT: Okay.

June: Now you said [pause] the masses are different but the acceleration is the same.
FT: And... [long pause] The force on the bigger mass will be 20 times bigger than on this one.

June: [pause] Okay [suspiciously]. So, how can the force be different?

(Interview Excerpt 1.9, March 3, 1999, lines 414-421)

Relying on her observations, June is able to conclude that the heavier object does not gain more speed during free fall. Choosing the word "constant" above to indicate that bigger object does not go faster is likely a mistake. What she means is that the two objects fall down together, having one's speed equal to the other's all the way down although they speed up. Her problem at this point seems to be how to fit "acceleration" in this picture. She observes different masses and their equal gain of speed during free fall, but she associates bigger force with bigger acceleration. When I say that the accelerations of the two objects are equal, but the forces on them are different and that's where she gets confused. According to her if the accelerations are the same so should be the forces or if the forces are different so should be the accelerations!

So, where is the problem? This understanding has followed her all along up until this moment despite my interventions, and it shows how resistant this non-Newtonian preconception is.

In brief her understandings can be formulated in this way:

i) the earth pulls the bigger objects more (bigger force),

ii) during free fall speed \( s \) is a function of both the height \( h \) from which the object is released and its mass \( m \). That is, \( s \rightarrow s(h, m) \).

iii) bigger forces exist in bigger masses or bigger masses carry bigger forces \( (F \propto m) \),

iv) bigger force means bigger speed \( (F \propto s) \),

v) acceleration is not at what rate the speed changes but rather just an indicator of whether or not an object is speeding up and moving faster.

Therefore, during free fall, the bigger the mass the bigger the force and the bigger the speed which results in acceleration (or more acceleration). Newton's second law states
that acceleration is directly proportional to the net force and inversely proportional to the mass which means that the bigger the force the bigger the acceleration, and given the same net force the bigger the mass the less the acceleration.

4.2.4.9 Things just fall down, no action at a distance

In the following parts of the interview June's confusion with gravity comes to surface. At the beginning she states that she thought the heavier objects would fall faster, but, after experimenting with dropping different masses from the same height, she observes that is not the case. However, when it comes to describing this acceleration and relating it to mass, height, and force (and gravity), she faces difficulties. One confusion is how gravity can know precisely how much force to apply on two different objects to make them to fall at the same rate. Gravity is not like a real force that someone applies on an object, but the force that causes falling is something inherent in each body which needs to be related to its mass:

June: It's like when things are falling you don't really need a force to get it somewhere, do you? [short pause] I mean there like is no.. there is no like me pushing down on the object it just sort of drops and then its .. its force or its weight carries it.

(Interview Excerpt 1.10, March 3, 1999, lines 473-477)

She is confused and uncomfortable with the idea that there is more force (of gravity) on the bigger mass than the small mass because she is so confident with the idea that gravity is uniform on all objects as a force which is "9 point 8 meters per second something":

FT: So, I mean what is confusing you?
June: [very long pause] I don't know how to say it. [chuckles] [pause] So, you are saying this one takes more force to get it to fall? To get it to the ground it takes more force? Is.. [pause]

(Interview Excerpt 1.11, March 3, 1999, lines 489-492)
4.2.4.10 Gravity is a special kind of force!

June expresses the notion that gravity causes things to fall down and is a constant force applied on an object at all points on its path during the motion. At the same time, she makes a distinction between gravity and the force that falls into the $F = ma$ category. When asked to comment on the amount of force on the 200 g and 10 g masses used to make free fall observations, June indicates that the force of gravity must be the same on both of them since they are hitting the ground at the same time when released from the same height, (June's *ad hoc* theory):

FT: Okay. So, do you think they have the same amount of force on both of them to arrive at the ground at the same time?

June: Through gravity? Yes! But like mass-wise, no.

(Interview Excerpt 1.12, March 3, 1999, lines 508-510)

June adjusts her theory of free fall by adapting it to her observations that she made during the interview. This new *ad hoc* theory shows that she gave up the idea that heavier bodies fall faster but only so she could keep her conception that more force means more speed. She needs to do that because if there were different forces on bodies with different masses, they would have to end up with different speeds when they reached the ground. Thus, June, now, distinguishes gravity as a special class of force which is the same on all objects such that all objects gain the same speed during free fall. Also, this is probably what she means by calling gravity a "constant" force, meaning 'having a uniform affect on all bodies.' In short, June relates force directly to speed, which can be formulated as $F \propto s$. It should be noted that this formulation is totally independent of the mass.
4.2.4.11 Different force but the same acceleration

Now, there is one objective to fulfill: to teach June why two objects with different masses hit the ground at the same moment when released from the same height. I want to help June develop an understanding that gravity is a force just like all others, and to explain free fall through 'uniform acceleration' rather than 'uniform force.' For this purpose, I ask June to compare the accelerations of the two masses during free fall:

FT:  What kind of acceleration do they have?
June:  They hit at the same time.
FT:  What is the acceleration? I mean what is the acceleration of this and of this?
June:  9 point 8 meters per second square.
FT:  The same?
June:  Yes!
FT:  Okay.

Interview Excerpt 1.13, March 3, 1999, lines 519-526

Since June associates acceleration with excessive force, she is hesitant to admit that the accelerations are the same. She then refers again to constant gravity: since the accelerations are the same, the pull of the earth (gravity) must also be the same on the two objects. Therefore, "the pull of the earth" does not mean the force but the displacement in unit time (as in the expression pulling an object a certain distance): if the pull is more, then the speed will be more. Since in this case "they hit [the ground] at the same time," the pull must be the same, leading June to state that "gravity is constant" on all objects. After making sure that June still keeps in mind that the two masses are different I give the example of weighing on a bathroom scale or measuring the weight of an object with a spring scale. My intent is to show that the amounts of matter are different in the two bodies (and, therefore, the forces of gravity), but not the pull, since the accelerations of the two bodies would be the same if dropped. June begins to articulate that the masses of the two objects (10 g and 200 g) are
different, so the forces due to gravity must be as well, since the accelerations are the same (as calculated by the formula $F = ma$). She states that the bigger object weighs more because the gravity is "pulling it down more," and here comes another important key point during conversation:

FT: Okay. And masses are different
June: Masses are different.
FT: So, therefore force is mass times acceleration.
June: So, force is different.
FT: So, force is different. Just like I weigh more than you weigh. Or, if I attach a spring scale I have a different reading than this one because the pull of gravity, the force of gravity, on bigger object is bigger because mass is bigger.
June: It is.
FT: Isn’t it? But why do you read more when you attach a spring scale on this one?
June: Because it weighs more.
FT: Okay. So, the gravity is pulling it..
June: .. pulling it down more.
FT: Yeah. But with the same rate.
June: Okay, there was where I was confused, because we are saying that "with the same rate" but it is actually different because it weighs.. it weighs different amounts.

(Interview Excerpt 1.14, March 3, 1999, lines 527-538)

This puts June in total confusion: Is gravity constant or is the pull more on the bigger object? And what does it mean that the pulls are different but the accelerations are the same or they are being pulled with the same rate? What does rate mean? If they weigh differently how can they fall with the same rate or vice versa? It looks like she does not understand what is meant by the expression "the same rate." The conversation continues with a concrete example:

FT: There is different amounts because..?
June: There is more matter to the 200 than there is to the 10.
FT: But not the acceleration?
June: Right.
FT: If you throw the 10 grams out of the fifth floor of the parking deck and me, we will hit the ground..
June: [chuckles].. at the same time
[both laugh]
FT: .. because it is not the mass which changes your position. It is acceleration, the rate of change of velocity right.
June: Okay... so..
FT: We are changing our position at the same rate, then we are changing our velocity at the same rate, therefore we have to arrive in the certain time period in the same place.

June: Okay.

(Interview Excerpt 1.15, March 3, 1999, lines 539-555)

4.2.4.12 Picking up speed during free fall

During all this qualitative reasoning exercise, the only formula that came up was Newton's second law \((F = ma)\). We have discussed no other kinematics formula during class sessions nor during this interview. For free fall, June had to use her intuition (e.g. tacitly assuming that the motion starts from rest \((s = 0)\) and hence the initial conditions for the two objects are the same). June extends this puzzle to a condition where the initial conditions are not the same:

June: Umm, so if we drop something from the fifth floor of the parking deck and drop something from the sixth floor of the parking deck at the same time..

FT: mm hmm ..what will happen?

June: Exactly..

FT: What will happen?

June: I don't know. [laughs]

(Interview Excerpt 1.16, March 3, 1999, lines 557-562)

She has a feeling that the one that starts from the fifth floor will hit the first and assures herself that the weights of the objects do not matter:
June: But, like where it is dropped from does matter.
FT: Okay. Because?
June: Well.. see when we drop it from higher it has more time to gather speed, but when we drop it from lower it has less of a distance to travel. So, I wasn't sure if the one floor difference and the dropping would the added speed would make it get there faster or the shorter distance would make it get there faster.

(Interview Excerpt 1.17, March 3, 1999, lines 570-577)

This is a perfectly legitimate argument. By putting up this question June is trying to make sense of how the "height" factors itself out during free fall since they already ruled out the argument that masses play a role for speeding up. They also observed that the higher the distance traveled, the faster the object hits the ground which indicates that the object is continuously gaining speed. Again they experiment and see that the lower one reaches the ground first. Now June proposes another experiment: Releasing an object "whose mass does not matter" from a slightly higher point and, as it reaches the lower one releasing the second from there. Before experimenting her reasoning is

June: The one that started earlier is gonna go faster.
FT: And hit the ground at the same time or earlier or later?
June: Hit the ground (pause) I would say hit the ground first. Because it had that extra second to start gaining the 9 point 8 meters per second no matter.
FT: Velocity
June: ..Yeah, no matter what the weight was.
(Interview Excerpt 1.18, March 3, 1999, lines 587-592)

When they do the experiment, June's prediction comes out right. Creating such mind-problems and successfully plotting a solution shows that June is now grasping some aspects of a scientific understanding of free fall. She no longer holds the idea that the mass of an object is a factor for speeding up during free fall. Instead, she states that regardless of mass, all objects are going to end up with the same speed and at the same time at the bottom.
4.2.4.13 Air resistance during free fall: "Being afloat on the air"

We then start discussing June's initial conception that feathers would drop slower than some other objects. June now thinks back and says maybe it was not such a good example because unlike other very light objects, such as a penny, a feather is "afloat on the air" during free fall. Thus, June notes another property of objects that affect their motion during free fall: solidness. By that she is probably referring to the density of objects. We experiment with this idea using a small piece of paper towel and a 10 g weight. As predicted, the weight falls much faster than paper towel. But when the paper towel is made into a small ball, the same piece now falls much faster than before, about at the same rate as the weight. June explains this new situation as "So, it is more aerodynamic, right?"

I make transition from here to the concept of friction and explain the two cases of the paper towel experiment in terms of air resistance. When the paper towel is unwrapped there is a resistance due to air which opposes motion (a force in the opposite direction to motion). However, the weight faces no such detectable resistance and moves a lot faster downwards. Wrapping the paper towel eliminates most of this air resistance, and the resultant motion is exactly the same as that of the 10 g.

4.2.4.14 A totally frictionless environment

Considering that one other draw back in understanding force and motion and related concepts might be the presence of friction in real life situations I ask June what would
motion be like in a totally frictionless environment. June responds in a natural way stating that once the motion is initiated it will continue:

FT: If there wasn't friction how do you get things move?
June: You just have to like initiate motion and then it just continues.
FT: You still need a force?
June: Yeah. I think so I mean it's not just gonna move on its own you have to start it. Something has to act on the mass to make it move.
FT: and if there is no friction what will be the speed of that object?
June: It is gonna be constant.
(Interview Excerpt 1.19, March 3, 1999, lines 746-766)

June does not require applying a force constantly in order to keep an object moving. She even predicts correctly what affect such a motion would have on velocity: it would stay constant. In a way, June here implicitly refers to Newton’s first law which states that "every material object continues in its state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed on it" (Hewitt, Suchocki, & Hewitt, 1999, p. 31)

The interviewer gives a concrete example of pushing a chair on ice, considering that ice, is close to a frictionless surface:

FT: ...and what would be the subsequent motion after I take my hands off it?
June: I think, if there is no friction it is just gonna keep going.
FT: With what kind of velocity? Will the velocity decrease, will the velocity increase, will it stay constant?
June: [pause] I don't know.. it is either gonna stay constant or it's gonna.. get.. or it's gonna increase. Because without friction there is to stop it is not gonna decrease, is it?
(Interview Excerpt 1.20, March 3, 1999, lines 771-779)

June attributes decreasing velocity to the cause of friction, but this time she is not sure what the velocity would be.

June: I know if you just.. if you just push something like you just pushed the chair on it, it stopped because like there is strength of your force went out like that was it was used up but without the floor it would pro.. like the friction between the floor and the chair to oppose that [pause] I would think the motion would continue. But, I [pause] But, I am.. I am still not sure if it speeds up or just gonna stay the constant rate because when we talked about the incline the constant rate made it speed up.
FT: Constant rate of what?
June: Constant rate of [pause] was it speed or was it not.. like.. it was like.. it was a constant net force.

(Interview Excerpt 1.21, March 3, 1999, lines 784-795)

Thus, what confuses June is revealed. In an earlier experiment, which she remembers from the classroom sessions, objects released from the top of an incline sped. June finds this case similar to pushing and releasing a chair on a frictionless surface. Obviously, June is not yet thinking in terms of concepts; rather, she is making analogies between cases where similar terms (i.e., friction, force, velocity, and acceleration) are used and which bear only visual similarity (someone pushing/releasing and object and cutting contact afterwards, and subsequent continued motion).

4.2.4.15 Motion implies force

I point out the similarity between motion on an incline and free fall and then try to pull June out of this confusion by bringing her back to the point where she said an object would preserve its speed on a frictionless surface (see excerpt 1.16). However, she goes back to the idea that motion implies force:

FT: Okay. If there is no force, what would be the speed? If there is no force, that means? June: It is gonna stop?

(Interview Excerpt 1.22, March 3, 1999, lines 808-809)

I direct her to think in terms of the formula $F = ma$ (Newton’s second law). Then she says, if there is no force on an object:

June: There is no acceleration.
FT: There is no acceleration. Therefore, that means in effect? [pause]
June: That it doesn’t move.
FT: Okay. Um..
June: After the fo.. is that it doesn't [excited laugh] Okay! It doesn’t speed up.
FT: Okay.
June: It stays [pause]..
June is always getting tricked by “no change” either in velocity or acceleration. Associating “not changing” (constant) acceleration, and no force with stopping. Although the same discussions were made in class and during this interview whenever she gives a prompt answer she is acting with her intuition rather than the concepts and the relationships between them. At the end the interviewer provides June a brief explanation to sum up the things by connecting force (a push) to acceleration and speed:

FT: Okay it is because you by pushing the chair on a frictionless surface you're applying an acceleration on it..

June: Okay.

FT: ..and that means the speed is going to increase..

June: Right.

FT: and then you release it you don’t add anything to its speed but it preserves its speed at the time of your release, right.

June: Okay. Yes.

(Interview Excerpt 1.24, March 3, 1999, lines 840-847)

4.2.5 Post-test

On March 18, 1999, approximately one month after the start of the Simple Machines unit following the spring break, students in the case study group took another conceptual test which included, again, items about force and motion similar to those asked on the pre-test (see section 4.2.1). The questions and June's responses related to force and motion are presented in Figure 4.3.
June's definitions of velocity, acceleration, and force are accurate and reflect the same ideas with almost the same words as those in her journal entry (see section 4.1.3). The second question merely asks her to apply those definitions by utilizing Newton's second law. She indicated that for a speeding up condition, the magnitude of forces in the direction of movement must be greater than those in the opposite direction, which may be friction. This can be interpreted as June requiring a net constant force in the direction of movement when an object speeds up on a horizontal line. The noteworthy thing is that June identifies increasing speed with a corresponding increasing acceleration.
Define the following concepts:

Velocity: the rate of change of position of an object

Acceleration: the rate of change of velocity of an object

Force: a push or pull that has the formula \( F = ma \)

What can you say about an object's acceleration and force(s) acting on it, if it is moving on a horizontal line and \( F = ma \)?

a) it is speeding up.

The acceleration is increasing. The mass is remaining constant. The forces are greater in the direction of the movement.

b) its speed doesn't change.

The forces acting on the object are constant as is the acceleration.

c) it is slowing down.

The forces acting on the object are decreasing as the acceleration is decreasing.

Figure 4.3. June's responses to post-test questions on force, acceleration, and velocity.

June's answer to the second part of the question also reflects the same kind of confusion. This time, constant speed is identified with constant acceleration. Additionally, she requires a constant force be applied in order to maintain a constant speed. This is probably due to her imagining a real situation where friction exists and cannot be totally eliminated. The question does not specify whether or not friction is to be assumed zero. However, Newton's first law requires that in either case the net force must be zero on an object moving with constant speed on a horizontal line.
For the case of an object slowing down June imagines that the forces on the object are diminishing which, in effect, diminishes acceleration. Therefore, she establishes a one to one correspondence between speed, force, and acceleration. According to her, these three variables are proportional, and a change in one of them calls for a corresponding similar change (increase or decrease) in the other two.

Newton's second law \((F = ma)\) requires that force and acceleration be proportional to each other, (as June noted in her journal entry previously mentioned); however, there exists no such relationship between force and speed. If friction exists in the environment, moving an object at a constant speed on a horizontal line would require simply overcoming the resistive force of friction by an equal force if the object is already in motion (Newton's first law). In this sense, motion implies constant force. However, reaching a certain speed would require accelerating the object (Newton's second law) from at rest by means of a net force (greater than the force of friction) in the direction of motion (Newton's first laws). Therefore, a constant net force accelerates the object. While the force of friction is independent of the area of the surfaces that are in contact, it depends on the nature of the surfaces and the weight of the object. If the object is heavy, the friction force can become so high that it requires a constant push. In such situations, objects stop dead almost immediately after release. On the other hand, lighter bodies, especially on smooth surfaces, cover a long distance before they come to a stop after they are pushed or pulled and released. Therefore, explaining motion according to laws of physics requires that one understands Newton's first and second laws and the role of friction during motion.
4.2.6 Tutoring Interview – II: The aftermath of the post-test

On March 22, 1999 I conducted the second tutoring interview with June in the fifth week of the Simple Machines unit (see table 4.1) just after the post-test (see Figure 4.3 and section 4.2.5). The interview lasted about 45 minutes and aimed at reviewing June's answers that she gave to the related questions on force and motion in the post-test. I discussed with June her answers on the test in an attempt to both probe her understandings and help her develop more scientific ones. Below is an account of this tutoring interview session, which includes both excerpts of the interviews and interpretations of June's understandings.

4.2.6.1 Relationships between force, acceleration and velocity

I started the session by pointing out that I like the definitions she gave for velocity, acceleration and force. I then focus on the second part of the questions in which applications of these definitions are required for various situations in which the observable (an object's speed) is given and its causes (the amount of applied force and resulting acceleration) are sought.

FT: Question is what you say about an object's acceleration and forces acting on it if it is moving on a horizontal line and it is speeding up, okay?
June: mm hmm.
FT: You say the acceleration is increasing the mass is remaining constant. We have this object, the forces are greater in the direction of movement. Why did you say the acceleration is increasing? It is speeding up. [pause] Acceleration might be increasing that's one way and what happens if the acceleration is constant?
June: Acceleration is constant .. It probably still speeds up.
FT: It probably still speeds up. Okay.
(Interview Excerpt 2.1, March 22, 1999, lines 24-32)

Whenever an object accelerates, no matter what the magnitude or change in acceleration, its speed must increase. Since June drew parallels between the magnitudes of
speed, acceleration and force in her response to post-test questions I want to clarify those relationships for her. The difficulty in understanding such relationships likely stems from a lack of proper understanding of the concept of acceleration, an understanding that requires more than merely reciting its definition. Therefore, I particularly focus on this key point and emphasize that constant acceleration means increasing speed.

When this idea was first presented during the case study group instruction (see section 4.2.2.3), it came as a surprise to the students and received a lot of resistance before finally being accepted. The same happens here again. Although from the formula June can infer what happens to acceleration given the change in force, she gets perplexed when knowledge is translated into speed:

FT: (...) and um if the acceleration is increasing what happens to F? The net force or the resultant force on the object.
June: It's probably gonna increase too.
FT: Yeah. If acceleration is constant and the mass is constant what will happen to F?
June: It'll be constant.
FT: OK. Now if acceleration is increasing and you are like pushing an object okay to increase the acceleration what do you need to do? [pause] Do you understand the question?
June: No.
FT: Like let’s say I am sitting in a chair with wheels and you are pushing me from back OK, and my acceleration is increasing due to your push..
June: OK.
FT: If my acceleration is increasing um what kind of force you are exerting on me, on the chair?
June: What kind of a force?
FT: I mean is it constant, is it getting smaller, is it getting greater each time?
June: um to make the acceleration increase the force has to be greater.

(Interview Excerpt 2.2, March 22, 1999, lines 32-48)

I emphasize that a continuous increase in net force on an object can bring about a corresponding continuous increase in acceleration. In the continuation of the dialogue, when I explain how Newton's second law is applied by discussing the formula $F = ma$, June seems to agree that a constant net force on an object will produce an increase in speed due to
constant acceleration. However, she cannot make the connection that a constant acceleration in the formula actually means speeding up:

| FT:   | Each time. |
| June: | Each time. |
| FT:   | Each time, it will get greater and greater. So, if you exert a constant force on, and my mass is constant in the chair, my acceleration will be? [pause] Like F is constant on one side of the equation and mass is constant, therefore, acceleration will be? |
| June: | Constant? [softly]. |
| FT:   | .. will be constant. So, I will be still speeding up, if a constant acceleration I have or in other words if you exert a constant force. |
| June: | [pause] Yes! But this equation won’t show it, right? This equation won’t show that you are speeding up. |

(Interview Excerpt 2.3, March 22, 1999, lines 49-58)

Obviously, June is perplexed here about understanding Newton's second law; she cannot make the transition from force to speed via acceleration. In the post-test, her answers clearly reflected that she established a linear relationship between speed, force, and acceleration, but she is still clearly having difficulty associating constant acceleration (and force) with increasing speed.

At this point I decide to focus on the equation $F = ma$ and go from there to the definition of acceleration in order to build a connection to speed:

| FT:   | If you put zero in this equation [in place of acceleration] what will happen? |
| June: | um it is gonna be zero. |
| FT:   | I mean, if the rate of change of your velocity is zero which means .. what does that mean? |
| June: | Acceleration is zero. |
| FT:   | Acceleration is zero and the rate of change of velocity is zero therefore your velocity is .. is it zero? Or? |
| June: | Constant. |
| FT:   | It is constant, right. Because it doesn't change. |
| June: | Right. It doesn't mean it has to be zero just means it's constant. |
| FT:   | If your acceleration is zero, it means your velocity is.. |
| June: | Constant. |
| FT:   | ..constant [at the same time]. Therefore, in this equation if the net force on an object is zero the acceleration is zero, right. Its mass cannot be zero. |
| June: | Right. [both laugh] |
| FT:   | Which means you can have either zero velocity, right? |
| June: | Yes. |
| FT:   | If it is a balanced situation everything remains constant. |
| June: | Okay. |
| FT:   | Or.. you are moving with .. if you are moving and your acceleration is zero ..?
June: Then it is a constant velocity.
FT: Yeah. Therefore, this equation implies that if you have zero acceleration you are.. from the definition you read that, right?
June: mm hmm.
FT: If your acceleration is zero, you are either remaining at rest or moving with constant speed.
June: Yep.
FT: And as you said the forces should be greater in the direction of motion but if you have a force in the direction of motion your acceleration is not zero right?
June: Right.
FT: Therefore your velocity ..?
June: Is not constant?

(Interview Excerpt 2.4, March 22, 1999, lines 63-98)

Hence, rather than relying on her intuition, June now has to think in terms of Newton's laws. The first law states that "an object at rest will remain at rest and an object in motion will continue in motion with a constant velocity" (that is, constant speed in a straight line) unless it experiences a net external force (or resultant force)," (Serway, 1990, p. 99). The first part of the first law defines the static equilibrium, while the second part defines motion under forces in equilibrium (zero net force) or motion with no applied forces (that of an isolated body which does not interact with its environment). Static equilibrium is more readily conceivable than the latter, because in real life there are always resistive forces (the forces of friction between surfaces) acting against any tendency towards movement.

On the other hand, inertia acts just like friction, and it is hard to distinguish between them in real life situations. Newton's second law states that "the acceleration of an object is directly proportional to the net force acting on the object, is in the direction of the net force, and is inversely proportional to the mass of the object" (Hewitt, et. al., 1999, p. 36). According to June's initial conception, Newton's second law has a form of $F \propto v$ rather than $F \propto a$, when in fact, the

* Throughout this study velocity will be considered on a horizontal line. Therefore, since there is no change of direction involved velocity and speed can be used interchangeably.
second law does not refer to velocity. The relationship between applied net force and instantaneous velocity is, therefore, inferred through a correct understanding of the concept of acceleration. Although, it has been observed that June retains the definition of acceleration in her memory, this knowledge has not yet become operational. When it comes to commenting on the concepts of force, acceleration, and velocity June uses her intuition rather than Newton's laws.

From excerpt 2.4 it appears that June is starting to grasp at least some aspects of Newton's laws. After noting the fact that for both cases in which the net force on an object increases (increasing acceleration) or remains constant (constant acceleration) the speed will be increasing, I ask June about a third case where speed will still increase: diminishing net force on an object (decreasing acceleration). For an object losing speed, June imagines intuitively that the forces on it should also decrease and vice versa. To probe further I ask her to comment on what would happen to the velocity if the net force on an object and hence the acceleration are continuously decreasing but not yet zero:

FT: Acceleration may be changing if you are pushing harder and harder each time..
June: mm hmm.
FT: .. but if you have a net force on an object you should speed up right?
June: Yes.
FT: So, the second case is its speed doesn’t change [refers to the post-test question]. You say "the forces acting on the object are constant as is acceleration." So, we just saw that if your acceleration is constant what will happen to your speed?
June: It will increase.
FT: It will increase, right.. If it is slowing down it is just the reverse of the first case. There should be some force resisting against you, against your motion, which you said the forces acting on the object are decreasing as the acceleration is increasing.
June: .. decreasing [June correct FT]
FT: .. decreasing actually. Let’s say the force is decreasing on an object, okay, but it is not zero. It is just decreasing.
June: Okay.
FT: Okay? Then what will happen to your acceleration? If you look at the formula your mass is constant..
June: Acceleration is going to be decreasing also.
FT: Acceleration is going to be decreasing also. What will happen to your velocity?
June: It's [pause] also gonna be decreasing, isn't it?
I characterize a slowing down situation as existence of a net force in the direction opposite the original motion. If a resistive force acts on the object, then it starts losing speed. On the other hand, June understands the same situation as the greater the force the greater the speed. Therefore, it naturally follows that if the net force starts decreasing on an object, it should slow down at the same time. The intermediary in this case is acceleration. June admits that acceleration is decreasing if the net force on an object decreases: the time rate of change of speed is decreasing. Hence if speed has been changing/increasing by x amount of units, it should then with decreasing force start changing/increasing by y amount of units, where x>y. However, for June decreasing force and hence acceleration mean deceleration.

June's preconceptions are so deeply rooted in her understanding of force and motion that she cannot easily replace them with what I have been trying to teach. It is observed that reciting a formula and/or a definition does not mean that there is a conceptual understanding behind it. June continuously shows examples of this behavior. After all the classroom discussions and tutoring interviews June still holds the idea that force is proportional to velocity (not acceleration).

**Interview Excerpt 2.5, March 22, 1999, line 99-120**

FT: It's umm.. Okay, let's say you are pushing me and we go 5 miles in one hour and if in each instant you are pushing me with a lesser force ...

April: Okay.

FT: Okay? What will happen to my velocity? We started with 5 miles and acceleration is decreased and getting decreased in each time. [pause] Do you think the velocity will change?

April: The velocity is the rate of change of position.

FT: Okay.

June: So, if you are pushing something but you are not pushing as hard [long pause] I would think that it is not gonna go as far but is it.. is it constant?

**Interview Excerpt 2.6, March 22, 1999, lines 121-132**

June is puzzled again and her main difficulty is a connection between acceleration and velocity beyond their definitions. I talk in terms of the physicist's "ideal world," while
June always thinks in terms of the "real world." When I say acceleration is diminishing, I am referring to the net force on the object, but June understands it as the "push" being reduced and friction always existing for all situations. I strive to bring June to a mode where she can think in terms of the ideal concepts and how they relate to the real world.

June merely adapts my explanations into her conceptual framework. Even though I emphasize that in the above example the figures represent the amount of increase in velocity and use the units of acceleration (length per unit time square), June perceives them as speed. This suggests that for her there is not yet a clear-cut distinction between acceleration and speed. In the above excerpt, June's summary of my long explanation is very revealing of her conception of the relationships between force, acceleration and velocity.
amount increase will be reduced. But you will still increase your velocity. [long pause]
Is it confusing?

June: I think it is confusing because it's like saying that we are going from 5 miles
per hour and then here you are going 4 miles per hour.. [see Figure 4.5]
(Interview Excerpt 2.8, March 22, 1999, lines 155-168)

Despite my efforts to convey the meaning of acceleration, June persistently maintains her
own. She may be trying to adjust my explanations to her scheme rather than adjusting her
understandings to my descriptions. June's last comment gives a clue to why she is still having
a difficulty. She treats acceleration as strength of speed; if the speed is losing strength, as she
characterized before by "velocity running out" that means it is decreasing. For her,
acceleration is the tendency of speed to increase or decrease: when acceleration is strong, speed
increases, and vice versa. I once more point out the difference between acceleration and speed;
acceleration is the rate at which speed changes:

FT: Is that the increase, the amount of increase, or the total velocity? [pause] If it is the
amount of increase, that is correct. But if it is total velocity your velocity is getting
increased. [pause] Does it make sense? [pause] No? [pause] Umm, how can I
describe that..
(Interview Excerpt 2.9, March 22, 1999, lines 171-175)

4.2.6.2 A creative solution: June's Population analogy

Up to this point in the tutoring interview, I have been trying to understand June's
conceptions about force and motion and particularly the relationships she had established
between them. Subsequently, I have discussed various situations that could illuminate the
meanings of the concepts and their relationships to one another. My main objective was to
determine and act on June's conceptions. But I was having very little success; I was
overwhelmed and perplexed because of the lack of progress and my inability to convey
meanings to June, when she created a novel analogy. It is not surprising that the analogy came from a field with which she was much more familiar.

**June:** OK, velocity is still increasing but it is not...

**FT:** ..it is not increasing as much...

**June:** ..of increase is not as much.

**FT:** Yeah. The amount of increase is not as much, because the acceleration is not greater as much.

**June:** Okay, I got it! It is like the population problems where when they say there is a decrease in population that doesn’t really mean that because there.. it just means there is a decrease in the rate of growth of population.

**FT:** If they say the population is decreasing that means that the population is decreasing. But if they say last year the rate of increase of population is 2% and this year it is 1% your population is still increasing but not as much as last year.

**June:** Great. Okay.

**FT:** Good analogy, I like that.

**June:** [smiles]

*(Interview Excerpt 2.10, March 22, 1999, lines 176-189)*

Remarkably, June has the same confusion in the population example. She admits that she had trouble understanding the rate of change of population and how it is related to the total population number. I explain that in this case acceleration is analogous to the increase rate of population while velocity corresponds to the population itself.

**FT:** The rate of change is not as much as before but you still have a positive change.

**June:** Okay.

**FT:** Your population, the total population is still increasing but not at the same rate as before but with a slower rate.

**June:** So, we still have increase but the rate is decreasing.

*(Interview Excerpt 2.11, March 22, 1999, lines 190-194)*

I then give additional examples from two countries. One of these countries has a decreasing population over the years while the other has a decreasing "rate of increase," but the two do not yield the same result, since in the latter instance, the population of the country still increases but this time at a slower rate.

**FT:** There are some countries in Europe like Hungary the population is decreasing with 0.01 percent or something like that. Every year if they have like ten million people the number of people in that country is getting reduced. But in Turkey the increase of population rate, the rate of increase of the population was like 2.2 per cent. It is now like 1.2-1.5...

**June:** So it is not growing as fast.
FT: Yeah it is growing, but it is not growing as fast.
June: Okay. So the velocity is still increasing but the rate of increase is decreasing.

*(Interview Excerpt 2.12, March 22, 1999, lines 205-212)*

The analogy that June has created works. But it is not so easy to get rid of the old habits of the mind. She still interprets an increase with a slower rate as a decrease:

FT: ..and for which case is this?
June: umm.. when I am slowing down. Is that..
FT: If the force on an object is getting reduced that means the acceleration is getting reduced and in that case we have this situation, [pause] Does it make sense?
June: So this is for when you still have a net force?
FT: Yep. In order to increase velocity in any way you have to have force.

*(Interview Excerpt 2.13, March 22, 1999, lines 213-220)*

FT explains June again the relationship between speed, decreasing acceleration, and diminishing net force on an object and then asks a question for which she needs to take into account previous history of the object (initial conditions) as well as Newton's first law.

June: We still have force but the acceleration is decreasing is that what you said?
FT: Yep, because force is decreasing. And let's say the force is getting decreased and decreased and decreased the net force on you or on an object becomes zero what happens at that point?
June: When your net force becomes zero?
FT: mm hmm. That implies ..?
June: That the acceleration is zero.
FT: ..acceleration is zero. That implies..?
June: That there is no, that the velocity is constant.
FT: Velocity is not changing. Whatever velocity you have before you will continue motion with that velocity.
June: Until that velocity runs out..

*(Interview Excerpt 2.14, March 22, 1999, lines 221-232)*

June here successfully translates force into acceleration and then acceleration into velocity, which is a positive indication of learning. But at the end of the above excerpt, she states that "velocity runs out," showing one of two things: June either ignores what the expression "net force" means or she considers velocity as something that eventually gets used up during motion. If the net force on an object is zero, then there is no force acting on it including the friction force and, from Newton's first law, an object in this state continues
its motion with its current speed. It is quite possible that June understands net force becoming zero as having no more pushes on the object while still keeping the existence of friction. Therefore, it is common sense that all objects, once set in motion, eventually come to a rest due to opposition of friction to the motion. I try to explain how that "running out" of velocity is possible:

**FT:** We now started with a force and that force decreased, comes to zero point, the force, which meant acceleration is zero, which meant velocity is constant. Because in your prior movement you have a certain velocity and you are now going with that velocity. And now let's say we have a resistant force, which opposes in the opposite direction of your motion, therefore what happens? It will give a negative acceleration or deceleration, which means you are slowing down.

**June:** Yeah. The rate of cha..

**FT:** ..Each time you are loosing from your velocity. Right?

**June:** Yes.

**FT:** ..and if you keep going with that kind of a force, which opposes your motion, you will end up with? [pause] First zero velocity, right? Because each time your velocity gets decreased, right? Is it confusing?

**June:** What happened to.. what happened to our acceleration? Acceleration was decreasing..

*(Interview Excerpt 2.15, March 22, 1999, lines 233-245)*

This pattern of force is illustrated as in Figure 4.4 (this figure was not used during the interview). Force first diminishes during a period of time between $t_0$ and $t_1$. Since force and acceleration are proportional, acceleration is doing the same, but the velocity keeps increasing; when force becomes zero between $t_1$ and $t_2$ acceleration becomes zero as well, which means the object is still moving but its velocity is not changing. At that point, a stable resistive force in the direction opposite the original direction of motion (such as friction or a resistive push) starts reducing the velocity at a constant rate. June wonders what happens to the acceleration under these conditions, and I explain that it becomes a constant negative acceleration (i.e. deceleration) due to a constant negative (i.e. opposing) force.
Figure 4.4. FT gives an example of a situation where force continuously diminishes first and then becomes constant in the opposite direction.

FT: Let’s say you have a constant force opposing your motion.
June: Okay.
FT: Okay? And what happens to your velocity in this case?
June: It’s going to decrease.
FT: It is going to decrease which means you are slowing down.
June: Right.
FT: Right?
June: Right.
FT: And if you keep going in that manner you will end up with at some point zero velocity right? Your velocity will be reduced, reduced, reduced, reduced and at the end your velocity will become zero.
June: And that happens when you are not moving?
FT: If your velocity is zero that means what?
June: You are not moving.
FT: You are not moving, because velocity is by definition?
June: Rate of change of position.
FT: If your position is not changing you are remaining at rest. Now, if we continue further like having the opposing force in the other direction after you stop you will start moving...
June: ..that way..
FT: ..in the other direction right?
June: Yes.
FT: As long as we have a force you will be?
June: ..moving in that direction.

(Interview Excerpt 2.16, March 22, 1999, lines 246-269)

Reversal of the direction of motion takes place somewhere between $t_2$ and $t_3$ in Figure 4.4 depending on the object's speed when it reaches $t_2$ and the strength of the
resistive force. I do not say in the above excerpt that the resistive force grows continuously during that period of time, only that "if we continue further like having the opposing force in the other direction after you stop." That should be understood as one force, which neither grows nor diminishes but stays the same. From this explanation, June infers since speed increases, so does acceleration. I conclude by stating the condition for a growing acceleration: a growing force.

FT: (…) moving in that direction and what will happen to your velocity?
June: Well, once it starts going that way your velocity is going to increase again.
FT: increase again.
June: and that means..
FT: in the other direction..
June: Yes, and then acceleration grows.
FT: You will have an acceleration. If you push harder you will have greater acceleration each time.
June: Yes.
(Interview Excerpt 2.17, March 22, 1999, lines 270-278)

4.2.6.3 Understanding motion in terms of acceleration

Figure 4.5 displays June's notes taken during this interview. In a way her notes are a summary of this tutoring interview since it shows where she was having difficulties understanding what I was explaining, specifically:

i) Acceleration is the change in speed, i.e. the portion added or subtracted from an object's current speed.

ii) Force is proportional to acceleration and not to speed. Therefore, any amount of net force on an object means that it has an acceleration, which brings about a change in speed.
iii) No net force on an object means that it has zero acceleration, i.e. no change in speed (Newton's first law). In such a case if an object is already in motion it will continue to move with constant speed; if it is at rest it will stay at rest.

The first two items above (and in June's notes) are paraphrases of Newton's second law, and the third item relates to Newton's first law. Figure 4.5 means that June at least came in contact with these ideas once more, but that does not necessarily translate automatically to a conceptual understanding.

Figure 4.5. June's notes that she took during the interview.
4.2.7 Word Association Task

All of the students enrolled in the course 'Fundamentals of Science and Engineering Design' were given a word association task on April 15, 1999, at the end of the course unit 'Structures and Stability'. This task was administered according to the procedures described in section 3.1.4.2. My purpose was explained in the booklet as an exploration of "what ideas you link together in your minds within the topic of simple machines." This was a timed task and students had 75 seconds to respond to each stimulus word.

To demonstrate how differently June could respond to the given word association task, the responses of April, Mae and Mike (see Figures 4.10-12) are included later in this section. These will serve as checkpoints while interpreting June's responses and in the analysis of her understanding of force and motion as revealed through her responses to the word association task. Since this research is a case study, it is not my intention to identify a "typical" and/or "anomalous" situation. Including other students' responses simply serves the purpose of analyzing June's understanding of force and motion through exploring and identifying meanings that all four students' responses convey.

4.2.7.1 June's responses to the stimuli in the word association task

The word association task included 12 stimulus words. Each pair of facing pages in the test booklet was dedicated to a single stimulus word; the word was presented on the left hand side of the facing pages while the right hand side remained blank. Figures 4.6 and 4.7 represent stimulus words and June's responses as they appeared in the test booklet: a
stimulus word at the top center of each page in capital letters followed by twelve lines starting with the same stimulus word. June's responses are presented in italics, her misspellings and unfinished words/expressions were retained exactly as they were written. In Figures 4.6 and 4.7 the numbers in parentheses next to the stimulus words at the top of each page did not appear in the actual booklet. They show the order of place that each stimulus word was presented.
Figure 4.6. The first six stimulus words used in the word association task and June's respective responses.
Figure 4.7. The last six stimulus words used in the word association task and June's respective responses.
4.2.7.2 Interpretation and analysis of June's responses

June's responses to the word association task will be analyzed in three ways. First, the number of responses she gave to each stimulus word will be evaluated; second, a categorical classification of the responses will be created; third, the overlaps between responses will be examined. In interpreting June's responses, these analyses will serve as a measure of her understanding and knowledge structure of the concepts represented by the stimulus words.

4.2.7.2.1 Number and nature of associated words for each stimuli

For each stimulus word, the numbers of associations made by all four students in the case study group are presented in Table 4.3 along with summary statistics. If the number of words associated with any given stimulus word is a significant measure of understanding by itself (White & Gunstone, 1992, pp. 151-152), then from Table 4.3 it can be concluded that June had a considerably better understanding of the concepts of lever, pulley, effort, vector, and mass as compared to force, weight, load, tension, work, mechanical advantage, and acceleration. These two groups of stimuli constitute, respectively, the ones with the number of responses greater than and less than the overall average number of responses.
Table 4.3. Number of associations June made for each stimulus word.

<table>
<thead>
<tr>
<th>Order in the booklet</th>
<th>Stimulus word</th>
<th>Number of associations made by</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>June</td>
</tr>
<tr>
<td>1</td>
<td>Work</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Load</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Acceleration</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Vector</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>Tension</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>Pulley</td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td>Mass</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>Force</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>Mechanical Advantage</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>Lever</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>Weight</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>Effort</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>58</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong></td>
<td><strong>4.83</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Standard deviation</strong></td>
<td><strong>2.44</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Median</strong></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><strong>Mode</strong></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td><strong>Maximum</strong></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td><strong>Minimum</strong></td>
<td>2</td>
</tr>
</tbody>
</table>

Although equal time (75 seconds) was given for each stimulus word the presence of a high degree of variation in the number of word associations is notable in June's responses. This non-uniform distribution shows that, first, there is a difference in the level of June's understandings of the concepts represented by the stimuli, and second, June did not take the task lightly by giving just a couple of responses for all stimulus words. For the five stimuli in the first group, mentioned above, June was in fact able to give 5-10 associations with an average of 7.20, while for the seven stimuli in the second group the number varied between 2-4 with an average of 3.14. Such a difference can be deemed an indication of a discrepancy in June's understanding of the concepts.
It is also noted that the stimulus words in the second group are frequently used in daily life with different meanings and connotations (except mechanical advantage) more often than those in the first group even though the stimuli in the first group received a greater number of responses. A quick glance at Table 4.3 reveals that June gave the least number of associations for the stimulus 'acceleration.' This might mean that among all the stimulus words she had considerably less understanding of the concept of acceleration. The other three students April, Mae, and Mike gave, respectively, 8, 9, and 8 responses for the stimulus 'acceleration,' which are very close to their overall average number of responses.

The reason for the small number of associations June made for the majority of the stimulus words may be due to several factors. One reason might be that there exist, in fact, no other words to associate with the given stimuli. This hypothesis is groundless when other students' high numbers of associations for each of those stimuli are considered. As White and Gunstone (1992, p.151) warn, a second reason might be June's cautious and reticent nature. Although I observed June being meticulous throughout the period of time I spent with her, this hypothesis cannot be sustained since she had given as many as 5-10 responses to 5 other stimuli presented in the same task. June's meticulousness, perhaps, is best reflected in her extended responses even though single word responses were requested. It is clear that she wanted to write many of her responses in a way that would avoid varied interpretations. All these considerations lead the researcher to think that there might in fact be a difference in June's level of understanding of the stimuli that she responded with less number of words and higher number of words.

One drawback of considering number of responses as a measure of understanding is that it does not reflect how closely the responses are related to the stimulus word in the
given context. For example, Mike included *employment, money, and job* in his responses to the stimulus 'work' (see Figure 4.12). Obviously, these associations are not appropriate in the context of simple machines; they are connotations of the word 'work' as used in daily life. Thus, considering the number of responses alone as a measure of understanding can be misleading. Therefore, besides the number of responses, the nature of those responses needs to be evaluated as well. Having concluded, based on number of responses, that June had a vague understanding of some of the concepts, I will now explore the nature of June's responses can be in greater detail (see sub-sections 4.2.7.2.2 and 4.2.7.2.3 below).

4.2.7.2.2 Categories of types of responses

It is noteworthy that June many times used expressions of word combinations rather than single words despite the directions clearly requesting single word responses (see Figure 3.1). This can be attributed to her meticulousness in nature. Indeed, extended responses are useful in probing what meaning a student attaches to a response word since a single word response might have different meanings depending on the context in which it is used (White & Gunstone, 1992, p. 147). Providing extended responses, on the other hand, narrows down the number of ways a particular response can be interpreted.

When June's responses are examined it can be seen that there are not any out of context associations for the stimuli. This is an advantage because no adjustment needs to be made in the number of June's word associations due to inappropriate responses.

June's responses were analyzed in terms of categories I constructed among the stimuli (see Table 4.4). This category set defines the relationships of the stimuli and the
responses to the context of the instructional unit. In establishing the categories, I received help from the instructor of the main course (see section 3.1.2), who was also a graduate student at the time in Science Education with a background in high school physics teaching.

Table 4.5 shows how the stimulus words themselves can be classified according to the category set given in Table 4.4. It should be noted that one stimulus word falls into more than one category. Figure 4.8 illustrates this property of the stimuli visually.

Table 4.4. Coding categories for the word association task.

<table>
<thead>
<tr>
<th>Category</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Related to force</td>
<td>F</td>
</tr>
<tr>
<td>Related to motion</td>
<td>M</td>
</tr>
<tr>
<td>Related to a Mathematical Construction</td>
<td>MC</td>
</tr>
<tr>
<td>Related to Properties of Matter</td>
<td>PM</td>
</tr>
<tr>
<td>Related to simple machines</td>
<td>SM</td>
</tr>
</tbody>
</table>
Table 4.5. A categorical representation of the stimulus words.

<table>
<thead>
<tr>
<th>Related to Force</th>
<th>Related to Motion</th>
<th>Related to a Mathematical Construction</th>
<th>Related to Properties of Matter</th>
<th>Related to Simple Machines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>Acceleration</td>
<td>Work</td>
<td>Mass</td>
<td>Lever</td>
</tr>
<tr>
<td>Effort</td>
<td>Force</td>
<td>Vector</td>
<td>Weight</td>
<td>Pulley</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Mass</td>
<td>Mechanical Advantage</td>
<td>Load</td>
<td>Mechanical Advantage</td>
</tr>
<tr>
<td>Mass</td>
<td>Force</td>
<td>Acceleration</td>
<td>Force</td>
<td>Work</td>
</tr>
<tr>
<td>Load</td>
<td>Effort</td>
<td>Acceleration</td>
<td>Force</td>
<td>Effort</td>
</tr>
<tr>
<td>Weight</td>
<td></td>
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<td>Tension</td>
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<td>Tension</td>
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<td>Force</td>
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<tr>
<td>Work</td>
<td></td>
<td></td>
<td></td>
<td>Load</td>
</tr>
<tr>
<td>Vector</td>
<td></td>
<td></td>
<td></td>
<td>Weight</td>
</tr>
</tbody>
</table>

Figure 4.8. Relationships among the stimuli and major categories.
The stimuli in the word association task that can more readily be considered as Newtonian concepts and June's responses to them are given in Figure 4.9, and a summary representation of June's responses to these stimuli is given in Figure 4.13. Numbers in parentheses show the order of place that the stimuli words were presented in the test booklet.

'Acceleration' was the second stimulus word presented in the word association task booklet. It can be seen from June's responses that she associated 'acceleration' only with change in speed. Since an object's acceleration is directly proportional to the applied force on it and inversely proportional to its own mass, associations with these two concepts are also expected. It is thought that Mae's responses portray a fuller understanding of acceleration within the Newtonian framework (see Figure 4.11), since she explicitly related it to speed, mass, and force. Therefore, it can be concluded from the number and nature of associations June made with acceleration that she lacks the expected depth of knowledge.

The stimulus 'mass' was presented later in the word association task booklet. June gave five responses: gravity, weight, matter, substance, and $F=ma$. This shows a better understanding of the concept of mass, as compared to acceleration, both in regard to number and quality of associations. $F=ma$ might indicate two things: June either associates the concept of mass only to this formula since it includes the term itself or to force and acceleration together in the context of Newton's second law. Considering June's alternative framework as revealed throughout spring 1999, however, the first indication seems more probable. When June's responses to this stimulus are compared to other students' (see Figures 4.10-12) it can be concluded that her list is richer than April's and Mike's. But again
Mae's response list shows a better understanding than the rest of the students. Mae made 9 associations, almost twice as high the number of other students' responses. She separately associated mass to force and acceleration. Moreover, her responses fall into all five categories which reflects a rich variety.

'Force' was a stimulus also included in the word association task, which was introduced right after 'mass' in the booklet. June made only 4 associations for this stimulus: $=\text{mass }\times\text{ acceleration, push, pull, exertion}$. As with acceleration, June made the fewest associations among the case study group students. Although June included the formula for Newton's second law it is again not clear if she thought about its relationship to the concepts of mass and acceleration separately or just remembered the formula. An examination of other students' associations for the stimulus 'force' reveals that, unlike June, all three of them included tension and compression among their first few responses. Only Mike included the words load, acceleration, and speed (in the same order) in his responses. April's only response that can be categorized under motion was the word 'motion' itself, and Mae's only response that could fall in this category was 'wheels.' Many of the associations made by April, Mae, and Mike were categorized under 'simple machines.'
### Figure 4.9
June's responses to selected stimuli and the categories that they belong.

<table>
<thead>
<tr>
<th>Work (1)</th>
<th>Load (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. effort</td>
<td>1. weight</td>
</tr>
<tr>
<td>2. force x distance</td>
<td>2. resistance</td>
</tr>
<tr>
<td>3. requires energy</td>
<td>3. output</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acceleration (3)</th>
<th>Vector (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. rate of change of velocity</td>
<td>F</td>
</tr>
<tr>
<td>2. speeding up</td>
<td>1. force</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tension (5)</th>
<th>Mass (7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. taught</td>
<td>1. gravity</td>
</tr>
<tr>
<td>2. strings always in tension</td>
<td>2. weight</td>
</tr>
<tr>
<td>3. opposite force acting on ends</td>
<td>3. matter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Force (8)</th>
<th>Weight (11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. = mass x acceleration</td>
<td>1. Mass</td>
</tr>
<tr>
<td>2. push</td>
<td>2. gravity pulling on mass</td>
</tr>
<tr>
<td>3. pull</td>
<td>3. downward component</td>
</tr>
<tr>
<td>4. exertion</td>
<td>4. easier to manage with simple ..</td>
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</tbody>
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<table>
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<tr>
<th>Effort (12)</th>
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<tbody>
<tr>
<td>1. [effort] force</td>
</tr>
<tr>
<td>2. exertion</td>
</tr>
<tr>
<td>3. energy required</td>
</tr>
<tr>
<td>4. decreases with simple mach.</td>
</tr>
<tr>
<td>5. [effort] distance</td>
</tr>
<tr>
<td>6. [effort] arm</td>
</tr>
<tr>
<td>7. input</td>
</tr>
<tr>
<td><strong>Acceleration</strong> (3)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>speeding up</td>
</tr>
<tr>
<td>directional</td>
</tr>
<tr>
<td>position</td>
</tr>
<tr>
<td>velocity</td>
</tr>
<tr>
<td>deceleration</td>
</tr>
<tr>
<td>change</td>
</tr>
<tr>
<td>distance</td>
</tr>
<tr>
<td>weight component</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Mass</strong> (7)</th>
<th><strong>Weight</strong> (11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>scalar</td>
<td>vector</td>
</tr>
<tr>
<td>no direction</td>
<td>downward</td>
</tr>
<tr>
<td>friction less</td>
<td>perpendicular component</td>
</tr>
<tr>
<td>component</td>
<td>more acting down a</td>
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Figure 4.10. April's responses to selected stimulus words and the categories they belong.
Figure 4.11. Mae's responses to selected stimulus words and the categories they belong.
Figure 4.12. Mike's responses to selected stimulus words and the categories they belong.

<table>
<thead>
<tr>
<th>Acceleration</th>
<th>3</th>
<th>Force</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>motion</td>
<td>M</td>
<td>tension</td>
<td>F</td>
</tr>
<tr>
<td>speed</td>
<td>M</td>
<td>compression</td>
<td>SM</td>
</tr>
<tr>
<td>inclined plane</td>
<td>SM</td>
<td>structures</td>
<td>SM</td>
</tr>
<tr>
<td>car</td>
<td>M</td>
<td>load</td>
<td>SM</td>
</tr>
<tr>
<td>gas</td>
<td>M</td>
<td>acceleration</td>
<td>M</td>
</tr>
<tr>
<td>pedal</td>
<td>M</td>
<td>speed</td>
<td>M</td>
</tr>
<tr>
<td>object</td>
<td>PM</td>
<td>friction</td>
<td>F</td>
</tr>
<tr>
<td>change of</td>
<td>MC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass</th>
<th>7</th>
<th>Weight</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>SM</td>
<td>Mass</td>
<td>PM</td>
</tr>
<tr>
<td>tension</td>
<td>SM</td>
<td>load</td>
<td>SM</td>
</tr>
<tr>
<td>compression</td>
<td>SM</td>
<td>tension</td>
<td>SM</td>
</tr>
<tr>
<td>object</td>
<td>PM</td>
<td>compression</td>
<td>SM</td>
</tr>
<tr>
<td>simple machines</td>
<td>SM</td>
<td>body weight</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lifting</td>
<td>SM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>carrying</td>
<td>SM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>supporting</td>
<td>SM</td>
</tr>
</tbody>
</table>
4.2.7.2.3 Overlaps between response lists

Figure 4.13 shows a summary representation of June's responses for selected stimuli according to their relevance to force and motion. All stimulus words shown are boxed. A bold line between two stimulus words denotes that at least one of them appears on the list of the other. A bold and underlined typesetting denotes that the response is either one of the stimulus words or it appears in another list similarly, which is deemed a weaker association. Dotted lines show the boundary of groups of stimulus words clearly associated with each other in June's response lists (see section 4.2.7.4).

An overlap between response lists of conceptually related words indicates a better understanding of the topic and an integrated knowledge structure within the domain. A sound understanding of force and motion can be detected if a number of overlaps between the responses to stimulus words force, acceleration, and mass are observed. Since June always thought that applied force on an object would be linearly proportional to speed, one would expect to see speed (or velocity) included among June's responses to force, but it was not. On the other hand, neither force, mass, nor the formula $F = ma$ appear among the responses to acceleration.
Figure 4.13. A summary representation of June's word associations.
4.2.7.3 Summary

It is significant to note that the stimulus word "acceleration" is almost exclusively related to change in speed as the summary representation illustrates (see Figure 4.7). Besides velocity, a close association of acceleration with force and mass is expected. In the test booklet the order of presentation of the stimulus words acceleration, mass and force were third, seventh and eighth places respectively. Although force took the last place among the three and June related mass to the formula for Newton's second law of motion ($F = ma$), she did not do so for acceleration.

Additionally, it can be inferred from the summary representation (see Figure 4.9) that while force lies in the same group with the stimuli vector, effort, tension, and work; mass lies in the same group with weight and load. Force and mass are related to each other via the formula for Newton's second law, $F = ma$, but, apparently acceleration stands apart from the rest of the stimuli. In June's list for acceleration only "rate of change of velocity" (first place) and "speeding up" (second place) were included. This can be interpreted in two ways. First, it can be noted that these two descriptors define acceleration appropriately (though they only weakly associated it with force and mass). Therefore, one can conclude that June's understanding of the concept of acceleration does not reflect any deficiency. On the other hand, one can look closely at June's previous and later use of the term, along with her understanding of it as revealed in interviews and other written documents in order to determine if such descriptors were mere rote memorization or if they indeed showed June's development in learning force and motion.
June clearly knew and could state the terms in the definition of acceleration as "the rate of change of velocity." Several times, including in the word association task, this knowledge of definition and terminology was visible. However, the data also revealed that even though June memorized and used the definition, she failed to respond according to the very same definition (see Figure 4.3 for the post-test questions and June's responses which set a very typical example). These considerations support the preliminary conclusion that in June's knowledge structure for force and motion, acceleration does not play the central role it does in Newton's laws.
4.3 Probing June's alternative conceptions: One year later

Via the data that was gathered during spring semester 1999, I obtained a considerable amount of information regarding June's alternative conceptions about force and motion. At the end of this phase, June seemed to have developed new understandings of force and motion, particularly in light of the 'population analogy.' It was considered to be a significant step in coming to understand the effect of force on motion and the role acceleration plays in describing motion. Since it was June who brought up the analogy and led the vivid discussions around it, I believe that a major breakthrough was accomplished in June's learning of force and motion.

I wanted to meet with June after substantial period in order to probe once more her understanding of force and motion. Thus, exactly one year after her first interview, the second phase of the study began which served the following purposes:

i) see if June was still holding the same alternative conceptions one year after,

ii) to determine if my understanding of June’s alternative conceptions and framework about force and motion was valid, and

iii) to explore what other information was available about June's alternative framework and learning of force and motion.

In the following sections the data collected during this phase of the study are presented together with my interpretations and analyses.
4.3.1 March 3, 2000: Administering the Uniformly Varied Force Questionnaire (UVFQ)

The 90-minute interview was held on March 3, 2000 exactly one year after the first interview with June. In this interview I used two problems and the Uniformly Varied Force Questionnaire (UVFQ) that I created based on June’s responses during the first phase of this study.

I initially introduced two questions: one regarding free fall of two objects of different weights and another regarding horizontal movement of two objects of different weights. Both questions involve constant forces on the objects which are traveling equal amount of distances in equal time.

These initial questions served as a "warming up" for the rest of the interview; they also probed how June would respond to virtually the same question introduced in two different contexts. The first two questions were followed by two more: if a constantly diminishing force is applied on an object, how does its velocity change? What happens if this force is reversed momentarily in direction after it reaches zero magnitude and starts increasing in strength in the same manner as it was diminishing? This event (a process of applying a force on an object in a certain manner during a period of time) was purposefully designed to portray June's understanding of force and motion. The questions about this event, which required a true or false answer, had a dichotomous nature representing two distinctly different conceptions – one in congruence with June's understanding of force and motion and the other representing the scientifically correct ones. I envisioned that the true/false answers would consistently form a pattern to disclose conceptions regarding force and motion.
Fifteen statements were provided about the event described above for June to respond either as true or false. These included:

i) relative magnitude of velocity at different times (statements 1, 2, 3, 5),

ii) direction of movement (statements 4, 5),

iii) position at the end of motion (statements 6, 7),

iv) the manner of velocity change during the period (statements 8, 9, 10, 11, 12),

v) the manner of acceleration change during the period (statements 13, 14, 15).

Below I am presenting the data and my interpretations.

4.3.1.1 Gravity: Constant force, constant acceleration?

The interview session starts with two questions to see how June understands free fall and motion on a horizontal line. The first question is about elapsed time during free fall for two objects of the same size and shape but different weights (see Figure 4.14). June quietly reads the question and tells me what she understands from the question by describing the problem situation and what is being asked. Her immediate answer to the question is:

June:  It's gonna be about the same for both balls.

However, her reasoning behind this quick answer is not so clear at the time:

FT:   Why do you think so?
June:  Because [pause] gravity is acting on both of them in the same manner regardless of their [pause] no [pause] I can remember having this discussion about the anvil and the feather, and um [long pause]

(Interview Excerpt 3.1, March 3, 2000, lines 9-13)
June looks to be having a good start for her explanation, but she is not confident on whether or not she is responding correctly. June relies more on her recollection of examples to conclude what happens at this specific case rather than reasoning using relevant concepts. Hence, I want June to refresh her mind and then lay out her reasoning for this case:
June picks the correct term "acceleration" to describe the situation. But it is not apparent what she means by that term. At this moment what she knows for sure, from the discussions the year before, are:

a) weight does not play a role in speeding up during free fall (anvil-feather example),

b) elapsed time is the same during free fall if the height from which the objects dropped are the same (parking deck example -see interview excerpts 1.12 and 1.13), and

c) acceleration is somehow related to speed and it is fixed ("9.8 something") for objects undergoing free fall.

The first statement above is observational, and the second one is a thought example which relies on experience as well. The third statement is a judgment (a factual piece of information) based on what June can remember about gravitational acceleration. At this stage June already knows the answer to the question, but what is important is how she patches these different bits of information together and how she uses them: her answer reflects a recollection of the result of the event (free fall) rather than a sequence of conceptual understanding. It is probable that she is working backwards from the ends to the means (since she knows the result, so she tries to fit a scheme to it). On the other hand, it is
not evident yet if June also regards the situation as "since the two balls are gaining equal speed (final speeds) within equal time periods (hitting at the same time), then the accelerations must be the same, and that gravity gives equal accelerations to all bodies undergoing free fall near the surface of the earth†.”

4.3.1.2 Motion on a horizontal line with constant force

At this time I introduce the second question (see Figure 4.15). June reads the question out loud and, wanting to make sure she understands it fully, re-reads it quietly to herself. After June finishes reading, I ask her what she thinks and about the question. June wants to know which object is heavier. She says that although it is indicated that the weights are different, she does not known which is heavier. I point out that objects are designated by W’s (their weights) as shown in the figure and in the wording of the question it is indicated that \( W_1 \) is greater than \( W_2 \).

† When universal law of gravity \( (F = m(GM/r^2)) \) is applied to this case together with Newton’s second law \( (F=ma) \) gravitational acceleration for objects under the influence of the earth becomes \( g=GM/r^2 \), which is independent of the mass of the object (here G is the gravitational constant, M is the mass of the earth, m is the mass of an arbitrary object under the influence of the earth’s gravity, and r is the distance between the earth and the object).
Two objects of different weights are pushed towards right with constant forces starting at the same instant. If they arrive at the same point at the same instant, what can you say about the forces acting on each of them ($W_1 > W_2$. Assume that friction between the objects and the surface is so small that it can be ignored.)

a) $F_1 > F_2$

b) $F_1 = F_2$

c) $F_1 < F_2$

d) Cannot be concluded

Figure 4.15. Two objects being pushed horizontally.

*FT: So why did you need that information?*
*June: Because if they were the same, then it would require the same force to push them the same distance.*

*FT: Okay.*
*June: But with one .. with $W_1$ being larger than $W_2$ it's gonna take more effort, or more force to push $W_1$ at the same rate as $W_2$, because $W_2$ is lighter.*

*(Interview Excerpt 3.3, March 3, 2000, lines 43-48)*

Again, June arrives at the correct conclusion but it is not obvious whether she is thinking intuitively or conceptually. I notice that June uses the term "rate." Both speed and acceleration are rates of change, the former being of position and the latter being of speed,
but the question only involves constant forces on objects, which implies only constant acceleration. Therefore, it is important to know to what she refers by this term.

FT: Okay, what do you mean by “the same rate”?
June: Well, it says that they arrive at the same instant. So, um force one \([F_1]\) is gonna have to be greater than force two \([F_2]\).

(Interview Excerpt 3.4, March 3, 2000, lines 49-51)

It is more probable at this point that June uses the term "rate" for change of position as in "pushing an object at the same rate". Another significant fact in the question is that friction is ignored. I ask if June considers this information at all and how.

June: Friction is like resistance to the force that you are applying. With friction it would be like pushing it across sand paper.
FT: Okay. So, it would resist if there was friction?
June: Um, when you say that you are ig.. basically ignoring the friction, it would sort of be like having W1 and W2 on wheels like on the smooth surface.

(Interview Excerpt 3.5, March 3, 2000, lines 55-59)

June’s responses to these two questions summarize her initial reactions to some of the concepts related to force and motion. Particularly important in this phase of the study is June’s understanding of the relationship between force and acceleration (Newton’s second law). This question is explored in the remainder of the interview in great detail by means of a questionnaire about an event, which I prepared based on my understanding of June’s alternative conceptions regarding force and motion as revealed in the first phase of the study.

4.3.1.3 Applied force diminishing at a constant rate: What happens to velocity?

I introduce to June the problem of “constantly diminishing force”(see Figure 4.16). I emphasize that the graph shows how the magnitude of an applied force changes in time and
ask June to read the question. After June finishes reading the question, I once more stress that at $t_3$ the force has its maximum value while at $t_2$ it completely vanishes; the direction of the applied force is then changed instantaneously at $t_2$ and the magnitude starts increasing steadily, finally at $t_4$ reaching the magnitude it had at $t_0$. I ask June to indicate whether each statement is true or false and tell why she thinks so (see Figure 4.16).
Magnitude of a force changes in time as shown in the figure above. At $t_2$ the direction of the force is changed instantaneously to the opposite way. When this force is applied on an object horizontally on a frictionless surface starting at time $t_0$ while the object is at rest which judgments below about the object's motion are TRUE or FALSE?
(At $t_0$ the force has its highest value, at $t_2$ it is zero and at $t_4$ it has the same value as it has at $t_0$, but reversed in direction).

1) **F** At $t_0$ where force becomes zero velocity will be zero, too.
2) **F** At $t_0$ and $t_4$ velocity will have its maximum value.
3) **F** At $t_2$ velocity will have its maximum value.
4) **T** At $t_2$ the object's direction of movement will be reversed.
5) **F** At $t_2$ the object will stop momentarily.
6) **T** At $t_4$ the object will be at the point where it started its motion.
7) **F** At $t_4$ the object will be at the farthest point with respect to where it began its motion.
8) **T** Right at $t_0$ the velocity will reach its maximum, and then on will gradually decrease.
9) **F** The object will start its motion with zero velocity, and velocity will steadily increase, and then velocity will steadily decrease until it becomes zero.
10) **T** The object's velocity will increase at a decreasing rate, and then will decrease at an increasing rate.
11) **F** The object's velocity will increase at an increasing rate, and then will decrease at a decreasing rate.
12) **F** The object's velocity will decrease at an increasing rate, and then motion will be reversed and velocity will increase at an increasing rate.
13) **F** The object has a constant acceleration throughout its motion.
14) **T** The object has a decreasing acceleration in the first half and an increasing acceleration in the second half of its motion.
15) **F** The object has an increasing acceleration in the first half and a decreasing acceleration in the second half of its motion.

Figure 4.16. The Uniformly Varied Force Questionnaire (UVFQ) and June's answers. After completing the questionnaire June replied to the first eight statements for a second time.
4.3.1.3.1 No applied force, no velocity (motion)

June: [reads statement 1] "At t sub 2 where force becomes zero velocity will be zero, too." [long pause] [Murmuring]
FT: What do you think? [long pause]
June: Umm, I think that for a split second while it is changing direction there might be a point where the velocity is zero.
FT: Since the force is zero?
June: Yeah.
FT: So, is it true or false? You can put a T or F.
June: Okay.
(Interview Excerpt 3.6, March 3, 2000, lines 83-90)

June realizes that the change of direction of the applied force takes place instantaneously, and decides that if t₂ represents a very short period of time (split second) then the velocity should also be zero during this time since applied force has zero magnitude at that moment.

4.3.1.3.2 The more the applied force, the more the velocity

June: [reads statement 2] "At t sub zero and t sub 4 velocity will have its maximum value." [pause] Um, I am trying to remember the relationship between force and velocity that we talked about.
FT: mm hmm
June: Because I know that's where the force is.. the force has its maximum value. [pause] I am gonna say true.
(Interview Excerpt 3.7, March 3, 2000, lines 91-95)

June’s answer indicates that she consistently equates magnitude of applied net force on an object to its velocity. Further, she thinks this is what we agreed on during their conversations the year before for the relationship between force and velocity. Correspondingly, from statements 1 and 2, if there is no applied net force, then velocity can't exist, let alone reach its maximum.
June: [reads statement 3] "At t sub 2 velocity will have its maximum value. [short pause] False.
FT: Because you think it will be zero, from the first one?
June: Yes.
(Interview Excerpt 3.8, March 3, 2000, lines 97-99)

This statement is the opposite of statement 1. So, it is natural that June thinks that it is false. It becomes gradually more evident as she proceeds responding to the statements that she is intuitively imagining a direct relationship between force and velocity.

4.3.1.3.3 Motion shall be in the direction of applied net force

Statement 4 was included in the questionnaire to determine if June would also think that the motion should be in the direction of the applied net force. Since the first three statements were designed to probe June’s understanding of the relationship between force and velocity, it would also be meaningful to confirm the responses to those statements by asking what directional relationship June envisions between force and velocity. Therefore, the problem was designed in such a way that the force changes direction in the middle of motion.

June: [reads statement 4] "At t sub 2 the object's direction of movement will be reversed." [pause] True.
FT: Why do you think so? [pause]
June: Because the direction of force is changed instantaneously to the opposite way.
FT: Okay.
(Interview Excerpt 3.9, March 3, 2000, lines 100-103)

Again, June maintains that since velocity diminishes and reaches zero in the first half of the motion, it should increase as the force increases in the second half of the motion. This reasoning indicates that motion is going to be in the same direction as the applied net force and the magnitude of velocity must be proportional to the strength of the net force. June
further confirms this line of reasoning by accepting statement 5 as true which is an alternate form of statement 1:

June:  [reads statement 5] "At $t_2$ the object will stop momentarily." I was hoping that's true.
FT:  Okay.
June:  Because as you're switching where the force is being applied there for a minute I think as you're I think it would stop for a sec.
FT:  Okay.

(Interview Excerpt 3.10, March 3, 2000, lines 104-108)

June’s responses thus far indicate that if an object moves under the influence of a net force, its velocity will be proportional to the magnitude of the force and the motion will be in the same direction as force. Logically this line of thinking would suggest that, given the form of applied force in the question, the object continually slows down as the strength of the force lessens, momentarily stops, reverses its direction, and (since the magnitude of force increases as much as it had diminished) the object covers an equal distance in the second half of the trip, returning to where it was at the beginning of the motion:

June:  [reads statement 6] "At $t_4$ the object will be at the point where it started its motion." [pause] True. Because if you think of it like flipping like folding the graph like all we are gonna get to $t_2$ and then you are gonna return and push it back.
FT:  Okay.
June:  [reads statement 7] "At $t_4$ the object will be at the farthest point with respect to where it began its motion." Well, considering what I said in 6 that makes 7 false. If I go with the same logic. [laughs] Because though it wouldn’t have to be at the point where it started because [long pause]
FT:  Is there any other option that you might think of?
June:  No, because it just changed instantaneously to the opposite way. I am gonna stick with what I said in 6.
FT:  Okay. So, equal amount of time this is the first half this is the second half.
June:  mm hmm.
FT:  Okay?

(Interview Excerpt 3.11, March 3, 2000, lines 109-121)
Velocity will reach its maximum when you push it the hardest, as you push it with less force it won't have as high velocity.

The next five statements (statements 8-12) are concerned with the nature of the change in velocity – acceleration. However, in those statements, the word "acceleration" is not actually used. Statements 13-15 explore the relationship between force and acceleration. In order to explore how June thinks, the statements were written in such a way that they included June's preconception, the scientific conception, and three distracters.

Statement 8 represents a situation in which a constant force opposes the motion of an object with an initial speed. When June reads it she is obviously being very careful in trying to understand its meaning and whether or not it reflected her thinking:

June:  [reads statement 8] "Right at t sub zero the velocity will reach its maximum, and then on will gradually decrease." [short pause] False. [short pause] Wait. [re-reads] "t sub zero, the velocity will reach its maximum, and then on will gradually decrease." Well, the velocity is decreasing here but then it increases again. So do you want up until t sub 2 or do you want all the way down to t sub 4?

FT:   Um, in the first half do you think the velocity will gradually decrease and then will gradually increase, is that what you think? [pause] Let's say up to t 2. [pause] If [statement] 8 was up to from t zero to t 2. (Interview Excerpt 3.12, March 3, 2000, lines 122-129)

June realizes that having velocity continuously decreasing from t₀ to t₄ would not fit her scheme. She also tries to match the type of variation in speed with the kinds of motion she observes in her everyday experiences: pushing something on a flat surface, up a slope, and down a slope. If something is pushed and released on a frictionless surface, the velocity will stay constant throughout motion, it will increase if there is a downhill incline, or it will decrease if there is an uphill incline.

June:  I think it depends like if what you're.. like if you are pushing this on a flat surface..

FT:  It's a frictionless surface.

June:  Frictionless surface, okay. So it's not like uphill or downhill or it's just a flat..
June finds more resemblance with this case to motion on a frictionless flat surface and forgets that the force is being applied throughout the motion (although at a decreasing strength). At the same time she still equates zero force at $t_2$ with stopping (zero velocity):

\begin{quote}
June: Okay, so, that makes me think that it's gonna stay constant from here and that it's not the velocity is not really gonna reach a maximum per se as it is gonna just go with the same rate till here until you stop it and start pushing it back.
\end{quote}

I want to understand why June wanted to change her mind, so I remind her that the force is being applied at all times; this is not a push and release situation:

\begin{quote}
June: Okay, so, that makes me think that it's gonna stay constant from here and that it's not the velocity is not really gonna reach a maximum per se as it is gonna just go with the same rate till here until you stop it and start pushing it back.
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\end{quote}

\begin{quote}
June: Okay, so, that makes me think that it's gonna stay constant from here and that it's not the velocity is not really gonna reach a maximum per se as it is gonna just go with the same rate till here until you stop it and start pushing it back.
\end{quote}
After this review of the meaning of force-time graph given in the question, June gives up movement with constant velocity idea – which would be true for an object pushed and released on a frictionless surface – and goes back to her original preconception corresponding to the situation described in the question:

June: Yes! And.. yes! The velocity will reach its maximum at $t_0$ when you push it the hardest and then as you push it with less force [pause] it won't have as high velocity.

FT: So, you think it is correct?

June: Yes.

FT: We considered it up to $t_2$ right?

June: mm hmm.

FT: So what do you think will happen between $t_2$ and $t_4$?

June: hmm. [pause] the negative here just means you are pushing in an opposite direction right?

FT: Correct.

June: Then, it's gonna be the reverse of what happened here you are gonna start building velocity as you increase your force.

FT: So it was stopped at $t_2$ momentarily and..

June: ..reversed!

FT: Okay, the motion reversed. Alright. [pause]

(Excerpt 3.16, March 3, 2000, lines 166-179)

Statement 9 is a distracter, written with a student in mind who would think that continuous application of a force is going to increase velocity without considering the constant decrease in force. This statement represents "a constant force/acceleration" situation.

June: [reads statement 9] "The object will start its motion with zero velocity and velocity will steadily increase and then the velocity will steadily decrease until it becomes zero." [re-reads the statement] "The velocity will start its motion with zero.. the object will start its motion with zero velocity and the velocity will steadily increase and then the velocity will steadily decrease until it becomes zero." Okay, now it is a frictionless surface. So is it gonna just go forever or?

FT: When are you asking?

June: When is this asking?

FT: Umm, let's read it together. The object will start its motion at $t_{sub \, zero}$, okay?

June: Yes.

FT: We start with zero velocity.

June: True!

FT: Okay. And velocity will steadily increase as you apply although the force is diminishing it says the velocity will steadily increase, okay. So, if you want.. graph what it says in 9 how would you graph it?
[June draws a graph, see Figure 4.17]

FT: In the first half after t 2 what happens it says? And then the velocity will steadily decrease until it becomes zero.

(Interview Excerpt 3.17, March 3, 2000, lines 180-194)

Figure 4.17. June’s graph for statement 9.

June: So, this is talking about the second half?
FT: Yeah.
June: Okay. So, the second half will be like this
FT: Or you can put it here like see, t 2 right.
June: Okay.
FT: The same interval these two? So, do you think this is what will happen?
June: [pause] No!
FT: No?

(Interview Excerpt 3.18, March 3, 2000, lines 195-202)

June rejects the idea that velocity will start from zero, increase until the force becomes zero, and then decrease until it reaches zero – quite a reversal of the form of force-time graph and her original preconception:

June: No, I don’t think that’s what’s gonna happen. Because not for what we discussed in 8.
FT: Okay. If you graph what will happen in 8 how would you graph it?
June: Umm.. [writes, see Figure 4.18]
Both graphs that June drew for statements 8 and 9 acceptably represent them. Graphs also show that June correctly understands the statements whether or not she agrees with them.

4.3.1.3.5 A change of heart: the velocity is going to be still increasing but at a decreasing rate.

Surprisingly, as soon as June reads statement 10 she agrees without getting any assistance from me, although previously she had agreed with statement 8. As she carefully reads the statement over and over again she faces a dilemma between this statements 8 and 10:
June: [reads statement 10] "The object's velocity will increase at a decreasing rate, and then will decrease at an increasing rate." [pause] I agree with that.

FT: If you graph it.

June: Wait, wait wait wait! [Whispering] And then decrease at an increasing.. Yes!

FT: If you graph it how would you graph it? Put t zero, t 2, and t 4.

June: [writes] Okay. [pause] wait wa.. wait. tsk, tsk, tsk, tsk, tsk, tsk, tsk

FT: What does it say the object's?

June: I am getting confused as to whether I think that the velocity is going to increase or if it's gonna just [long pause]

FT: Just what?

June: Does that mean in general? Like whenever it is increasing or does that mean from t zero?

FT: From t zero.

June: [Re-reads the statement] "From t zero the object's velocity will increase at a decreasing rate."

FT: What does that mean increasing at a decreasing rate?

June: Means it is gonna be still increasing but that it's increasing by smaller and smaller increments. So like the first time it is gonna increase by like 10, and then the second time it is gonna increase by 8 and then 6 and then [pause]

FT: Why would this happen?

June: Why would [murmuring]

FT: Like why would it happen in this fashion?

June: Because you are applying less force each time you push.

FT: So that means?

June: That the velocity is going to be still increasing but at a decreasing rate.

(Interview Excerpt 3.20, March 3, 2000, lines 221-243)

June understands and agrees with the statement together with a suitable reasoning. However, going directly from force to velocity is tricky. Her earlier statements in spring 1999 indicate that June’s notion of acceleration consisted of a binary indicator of speeding up rather than a measure of how velocity changes. Now she talks about "rate of change" of velocity by linking it to force, which is a very positive development for her understanding.

This last point is worth more exploration:

FT: So, how do you go from force to velocity? I mean what do you think?

June: [very slowly whispering] [inaudible] force to velocity. I wish I could remember the formula for [pause]

FT: Between force and velocity?

June: Yeah! So that I could remember the relationship, because honestly I don't. I mean I am thinking that you know applying a force to something is gonna increase its velocity. Is.. [short pause] the force times distance? What is force times [short pause] nothing. tsk, tsk, tsk, tsk

(Interview Excerpt 3.21, March 3, 2000, lines 244-250)
Although she already provided an explanation, June is now searching for a formula which directly relates force to velocity (assuming a formula exists which has force as a function of velocity or vice versa). Unfortunately, there is no such formula. The relationship between force and velocity is defined by Newton’s second law \(F = ma\) where acceleration is \(a = \Delta v/\Delta t\). Perhaps this is why the Newtonian notion of acceleration did not exist in June’s preconception. She had been relating force directly to velocity by skipping the concept of acceleration and here she does it again:

\[ \text{FT: } \text{Let me ask you this question. Let's say on ice again if you push something, which we assume, when we say on ice, a total frictionlessness. When you push an object like a cart like this with the same constant force how would you describe its motion? What would happen to its velocity?} \]

\[ \text{June: } \text{Umm.. It's gonna [pause] I am trying to decide if it is gonna be constant or if it is gonna be increasing. [pause]} \]

\[ \text{FT: } \text{According to what you are trying to decide? What would be your criteria?} \]

\[ \text{June: } \text{[pause] As to whether it is going to keep gaining momentum as it is going across this very slippery surface or if it is gonna just travel at a constant rate. And I think it is gonna be constant because you'd have to be adding more force for it to increase. I guess not just gonna increase on its own because I mean [pause]} \]

\[ \text{FT: } \text{So, to increase the velocity you need to push harder?} \]

\[ \text{June: } \text{Yeah!} \]

(*Interview Excerpt 3.22, March 3, 2000, lines 251-262*)

June thought statement 10 was true, but, at the same time, her intuition predicted a constant velocity for a constant force. An expert would immediately realize that constant force means constant acceleration, but June does not posses an accurate notion of acceleration, and she keeps relating force directly to velocity.

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\[ * \text{ This formula represents average acceleration during a time period } \Delta t. \text{ As } \Delta t \text{ becomes infinitesimally small (} t \to 0 \text{) the formula for instantaneous acceleration is given by } a = dv/dt. * \]
At this point I decide to go over statement 10 and illuminate how June understands it and why she thinks it is true or false (she already said she was leaning towards statement 10 when she read it the first time but it contradicted her original non-Newtonian preconception). To do so I ask June to draw a graph for the kind of change described in statement 10. She loves the idea of making a bar chart for variation in velocity over time from $t_0$ to $t_4$ corresponding to the force-time graph given in the question for the same period.

June: [pause] [whispering] increasing at a decreasing rate. Umm.. So like in [long pause] Okay so if it increases by this much the first time..

FT: mm hmm

June: ..then second time it is still gonna increase but by not as much. [draws a bar graph] [see Figure 4.19 below]

FT: Okay. That part the extra part

June: Yeah!

FT: ..is less than the first one?

June: Yeah!

FT: Okay.

June: ..and then, it is still gonna increase again but by only a fraction of this top part that was added on to this part.

FT: Okay.

June: Want me keep going?

FT: And it is till $t_2$ it says and then will decrease at an increasing rate.

June: [Repeats] Decrease at an increasing rate, okay. So, it's just.. it is gonna be like a normal curve. It is gonna go back down like just decrease a little the first time and then little more and there'll be decreasing by a lot.

(Interview Excerpt 3.23, March 3, 2000, lines 281-297)

Figure 4.19. June's graph for statement 10.
4.3.1.3.6 Confusion with force and velocity

The shape of June’s graph and the fact that she uses the "normal curve" idea to describe the curve for velocity-time graph described in statement 10 led me to conclude that she understands what is meant by the statement. The question is which statement June thinks is true and why:

FT: So, do you think that’s what will happen to the object’s velocity or is this true or false? You said true I guess, right?
June: Yeah.
FT: So does this contradict with what you said before?
June: I feel like it does. [both laugh] I am getting a little confused actually, umm.
FT: What confuses you?
June: I am just trying to remember what I had.. what I had done in the first couple. Talking about maximum like where the velocity is gonna be maximum like I said it would be maximum at t sub zero and t sub 4 but then I am saying that it’s.. Nope! I am still okay. Because I am saying it is still increasing and still decreasing, but [pause] tsk, tsk, tsk, tsk [draws] No, because then when it decreases at the end the velocity will be down here according to what I said above, right?
FT: mm hmm. Will diminish.
June: Yeah. [pause]
FT: Why would this happen? I mean is there a reason that the velocity will take such a curve?

(Interview Excerpt 3.24, March 3, 2000, lines 298-312)

June wants to be consistent with what she had said previously and tries to find a way to do so, but she notices a similarity between the graphs she drew of statements 9 and 10:

June: This matches with 9. And I said 9 was false.
(Interview Excerpt 3.25, March 3, 2000, line 313)

This confuses her because she rejected statement 9 at first and accepted statement 8 before. Now, statement 10 looks more plausible but it contradicts what she has been thinking would happen. In this confusion she decides to see what other options are available before she makes up her mind, and she says she wants to read statement 11 before going any further.

June: [reads statement 11] “The object's velocity will increase at an increasing rate, and then will decrease at a decreasing rate.” Well..
FT: If you were to graph that one?
June: [pause] [draws] It is gonna increase like crazy.
FT: Increments will be greater then the first one.
June: Yeah! [amused]
FT: This is.. yeah. Something like that [pointing to her drawing].
June: [reads the statement] "And then gonna decrease [slowly enunciating ] at a decreasing rate." [pause] So it is not gonna decrease as [pause] it is gonna decrease by smaller amounts each time.
FT: mm hmm.
June: So, like it's just barely gonna decrease. Is that.. but it will still be decreasing.
FT: mm hmm.
June: So, like I guess actually the first time at might need to decrease like crazy so that [pause] [draws see Figure 4.20]
FT: The decrease will be smaller.
June: Yeah.

(Interview Excerpt 3.26, March 3, 2000, lines 323-338)

Figure 4.20. June’s graph for statement 11.

The shape of the graph and June’s description of why it takes this form are consistent with the meaning of statement 11. But again the question is which statement to choose and why.

FT: Do you think this is what is gonna happen?
June: It is still asking the same thing that confuses me in 10. The fact that it's saying that it's gonna increase and then it is gonna decrease. [long pause] Because then we say if it was a frictionless surface it wasn't gonna decrease at all unless you stopped it. The velocity or the force? What are we talking about? [whispers] Oh my gosh. [gets perplexed] [laughs]
June now focuses on statements 9, 10, and 11 without categorically rejecting any of them. All three statements describe the motion as an increased velocity in the first half and a decreased velocity in the second half, but they do so in different manners. Although she disagreed with statement 9 right away, statement 10 caused her to re-think the process. What confuses June now is motion on a frictionless surface (an ideal imaginary situation), and the cause(s) of decreased velocity.

June always intuitively associated slowing down with some sort of dissipating entity which gets imparted to an object once it starts moving. In Newtonian terms a moving object acquires an initial velocity which only gets reduced by a counter-acting force on the object (Newton’s first law). June’s difficulty is thinking about moving objects in terms of her everyday experiences and imagining that what is passed to an object through a sudden push (applying a force) is the strength of the push, like a certain amount of fuel, that gets used up during motion. This source of confusion is revealed in the last quote above when June said “… if it was a frictionless surface it wasn't gonna decrease at all unless you stopped it. The velocity or the force? What are we talking about?” Obviously, June is trying to decide here what the friction reduces. She was originally thinking that the greater the force, the greater the velocity, and friction reduces the force on an object which in effect reduces the speed, since force is the cause of speed, and motion can not be conceived without force. Force implies motion: where there exists no force, there can be no motion. This course of developments during the interview directs me to provide some clarification to June as to what friction means and how it affects motion:
FT: ... what will happen if you push a cart? Without obviously there is no resistance to its motion.
June: Just gonna keep going.
FT: What will happen if you just push and leave it?
June: [long pause] Thinking about when I ice skate if I just push off something and go [pause] I slide for a while, but then I stop.
FT: Let's think about the outer space.
June: Okay.
FT: Like if you throw a stone, what will happen to that stone?
June: It's just gonna keep going.
FT: There is no resistance.
June: Yeah.
FT: There is no friction. So when we say there is no friction it is more like that situation.
June: Okay! So, then if you just push a cart across the ice it is gonna keep going. It is not gonna stop.

(Interview Excerpt 3.28, March 3, 2000, lines 346-359)

Newton’s first law defines uniform motion while the second law defines motion under a net force; indeed the second law is a natural and necessary extension of the first law. In situations where she needs to discriminate between the first and second laws, June gets confused. What situations are subject to which rules (Newton’s laws)? This indicates that even though the question emphasizes that the friction is ignored, June associates such a frictionless situation to her lived experiences where friction is not and cannot be totally eliminated. Therefore, the outer space idea makes more sense in this context.

4.3.1.3.7 Acceleration: The level of speed or time rate of change of speed?

In addition to understanding how friction acts on objects and what it means to be frictionless, June must know how the velocity will change during motion if an object is pushed and released on a frictionless surface (i.e., whether to apply Newton's first law or the second law and how):

FT: What will be the velocity [of the cart mentioned above]? Velocity will be increasing, decreasing, constant?
June: [long pause] I am trying to think about when an object falls now and how
[pause]
FT: Like the first question?
June: Yeah.
FT: So, what happens to its velocity? Like for example, how can you compare the velocity
in the mid-way, in the quarter-way, and the three fourths, okay? Let's say this is t 1, t
2, t 3, and t 4 starting from t sub zero. So, at t sub zero the velocity is..
June: Zero.
FT: ..at t 1?
June: 9 point 8.
FT: ..if it is one second.
June: Okay.
FT: And t 2 the velocity
June: [pause]
FT: Is it gonna be the same or?
June: It is gonna increase. [murmuring] tsk, tsk, tsk 9 point 8 meters per second.
FT: Per second square actually that is.
June: [Repeats] Per second square.
FT: It is what?
June: Acceleration.
FT: Okay. And acceleration is?
June: [softly] Velocity.
FT: I mean what does acceleration mean to you?
June: The rate of which something, the speed [long pause] something [pause] equals
m a.
FT: You are trying to remember a formula?
June: Well it.. yeah.
FT: What does acceleration mean to you?
June: [slowly enunciates] Ac-ce-leration. Like an accelerator in the car like umm.. the
rate with which something speeds up or [pause] covers a faster distance..
[repeats] covers a faster distance.. covers ah a larger distance faster. Cover.. I
don't know.

(Interview Excerpt 3.29, March 3, 2000, lines 360-389)

As before June tries to relate new cases either to her experiences or to the cases that
came up previously. She intuitively predicts that a falling object will continually gain speed,
and she struggles to understand similarities and differences between free fall and motion on
a horizontal line, which were the first two questions posed at the beginning of this interview
session. It is noteworthy that although she initially defines acceleration as "the rate with
which something speeds up," she quickly retaliates and reveals what she really understands
by that: the rate with which something covers a larger distance faster. The meaning of this statement is
that if starting from rest, the object has to change (increase) its speed more quickly in order
to cover a distance in a shorter time. On the other hand, it can also mean faster objects cover distances in a shorter time. Although the former is consistent with the scientific definition of the term acceleration, the latter is not. It is more probable that June thinks of acceleration as the level of speed rather than how fast speed changes. Therefore, if an object has a greater speed, it has more acceleration. Such a definition of acceleration is quite different than the scientific term because it does not refer to change in velocity at all.

In order to further probe what June thinks of acceleration, I ask a question in which two balls of the same size and weight undergo free fall but one is released from the first floor of a building while the second is released from the second floor. The second ball is released first and, exactly at the time it reaches the first floor the other ball is also released. Which one will hit the ground faster? After June indicates that she understands the question, I ask what she thinks and how?

**June:** [laughs] I am thinking I am trying to figure out if this one is going to have picked up so much speed that it's going to hit first or if since in the sense they are dropping from the same height at the miss point on if they are gonna hit at the same time. [pause] I am thinking that this one is gonna hit first and I am not sure that it is correct but my reasoning is that if you drop something [pause] if you drop a penny off the Empire State Building you see that it hits.. like if it hits someone down below it would kill them and it went through their skull. So I was just thinking about it must accelerate to such a rate that it's.. it's being pulled to the earth with such a force that it's like dropping.. it will be like dropping an anvil on someone's head from right above them instead of dropping a penny on someone's head. So, I am just trying to think about, I guess it has to build up a great rate of speed so I am gonna say this one hits first.

**FT:** So you used acceleration to describe the motion of this new ball.

**June:** Yes!

**FT:** So what does acceleration mean in this context?

**June:** [slowly enunciates] Ac-ce-leration means [pause] the rate of increase of motion. Is that.. the [pause]

**FT:** Increase of motion?

**June:** Increase of speed.

**FT:** Okay.

**June:** Yeah. Motion meaning falling down with speed.

*(Interview Excerpt 3.30, March 3, 2000, lines 405-423)*
While talking about speeding up during free fall, June uses "accelerating to such a rate" and "building up a great rate of speed." By these descriptors, she means the act of coming to move with high speed, and she defines acceleration as "the rate of increase of speed." For the case of free fall, June’s use of acceleration is consistent with the scientific definition of the concept since she refers to change in speed. What is more surprising is that she refers to the difficulty of stopping fast moving objects even though their masses may be quite small. Force is alternatively defined as the time rate of change of momentum: \( F = \frac{d(mv)}{dt} \). If mass is constant and velocity is high, the force needed to stop a moving object will become rather strong since it will have to experience a huge amount of acceleration in an infinitesimally small period of time. This should not be confused with the acceleration during free fall due to gravity, which is constant at all times for all objects and given by 9.8 m/s\(^2\).

Further conversation on free fall by examining different cases gives rise to the sense that June understands free fall fairly well. She refers to change in speed and building up speed during free fall.

FT: So, consider yourself jumping out from the first floor or the second floor which one would you prefer?
June: [laughs] The first floor!
FT: Why?
June: [laughing] Because that, well I don't have as far to travel and won't hit the ground as hard.
FT: If you compare jumping out from the first floor and the second floor how do you compare your speed in each case?
June: Well, you don't have as long from this distance to build up the speed. So, it is not gonna be as great as here when you just keep, your speed just keeps mounting and mounting until you hit.
FT: Let's say you have something.. something like that those models [mannequins]..
June: Okay.
FT: Okay, if you drop one from the first floor and I drop one from the second floor what will happen to yours and to mine?
June: You are dropping one from the second floor? You are just gonna hit before mine will.
FT: Okay. In the case mine reaches the same height as yours?
June: Yeah.
FT: Okay, other than that what's...
June: What? Okay, mine..
FT: What's gonna happen to them? Which one is more likely to break?
June: Yours.
FT: Mine?
June: It is gonna hit with a greater impact.

(Interview Excerpt 3.31, March 3, 2000, lines 424-445)

4.3.1.3.8 Free fall and motion on a horizontal line:
how do they compare?

After reviewing the concept of acceleration and free fall, I draw June’s attention once
more to the worksheet statements 10 and 11. June attempts now to reconcile the two cases,
namely free fall and motion under the influence of a constant net force on a horizontal line,
that she has been regarding as distinctively different. She is aware that what causes motion
during free fall is gravity and it does not act to move objects on horizontal surfaces.

June: So there.. there is an object make the same.. it doesn't really make the same
transition though from like falling to sliding horizontally, does it? Because
there is no gravity acting on it. You know what I mean?
FT: mm hmm. I guess. Tell me more about it.
June: Umm.. the 9 point 8 meters per second squared is the factor of gravity, isn't it?
It's like the.. So, that really isn't acting on the direction of motion that we are
talking about when we are talking about pushing something across the
horizontal surface like gravity is still pulling downward on it but you said it is
frictionless so we are sort of considering that that's not there. So, gravity isn't
increasing the rate of that object moving horizontally on the ice.
FT: Okay. So, it is your push.
June: Yes. So, that's why I am wondering if it increases or it is still the same?
FT: When gravity acts on these balls that we just considered, is gravity constant or is it
changing, increasing, decreasing?
June: Gravity is constant.
FT: Okay. So what is gravity?
June: Gravity is a force that [pause] I want to say it pulls on objects depending on
their [pause]
FT: What did you wanna say?
June: I wanted to say that it depends on their mass like how much they are effected
by it.
FT: Then you stopped, why?
June: I stopped because if it is constant then it.. like gravity can't like decide [laughs]
[pause] But it is all about like [pause] I guess in a sense the force that the
object directs downward. Like it.. that's it's directing it's mass downward sort of so..

FT: I mean what is confusing you now? Are you trying to make a transition from falling objects to..

June: Yeah.

FT: ..pushing on a frictionless horizontal surface?

June: Yeah.

FT: How it is similar or different?

June: [pause] It's different because of the effect of gravity. [pause]

FT: What do you mean?

June: When an object is falling [pause] gravity plays a bigger role. [pause] But when it is moving like horizontally gravity isn't working it like it is already on the surface it is not gravity is not..

FT: Instead to move an object on a horizontal surface you need to push it, right?

June: Yeah.

FT: So, is this push comparable to the pull of gravity?

June: What would be in the opposite [pause] part? Like gravity is like pulling it.. it will almost.. gravity is pulling it in the first [inaudible] is like a push.

FT: Or like I mean you have a string attached to a cart and you are pulling.

June: Yeah. Yeah that would be comfortable. Umm.

FT: With the same constant force?

June: Yes.

FT: What will happen to its velocity?

June: It will increase. [pause] I don't know. Let me think. [pause] See you are asking if I can have the same role as gravity horizontally if I am pulling with the same force on the..

FT: ..on an object?

June: [pause]

FT: Is it contrary to your experiences or what's confusing you?

June: It's just that same question as to whether the velocity increases or stays constant.

(Interview Excerpt 3.32, March 3, 2000, lines 447-508)

At this point, June is experiencing a great deal of difficulty imagining motion in a situation where a constant net force is applied on an object. She is torn between increased speed, which the school knowledge says would happen, and constant speed, which fits better her everyday experiences. It looks like the source of difficulty stems from eliminating friction on earth and imagining this as an ideal situation as usually given in physics problems. Hence, I ask June what effect would a constant net force have when applied to an object in the outer space, since ideally one can think of a remote spot in the outer space where no forces, not even gravity and friction, act on objects:

FT: Okay. How would that happen in the outer space?
June: How would..?
FT: If you continue to push the same object with the same force. No friction at all.
June: [pause] Well, the very first push will send that thing moving constantly forever anyway. So I guess me adding successive pushes is gonna increase it.
FT: Increase what?
June: Increase its rate of movement. So, increase its velocity.
FT: Okay. So when we come back on earth and let's say we are on ice and there is no friction and you are pulling
June: [laughing] It's gonna be increase. Okay.
FT: the velocity is..
June: gonna increase.
FT: Continually?
June: If I keep applying the force, yes.
(Interview Excerpt 3.33, March 3, 2000, lines 509-522)

Thus, outer space idea immediately makes sense to June and helps her conclude how the speed of an object would change under the influence of a net constant force. I want to make sure that June is now able to apply Newton’s first and second laws, so I ask her a question where a constant force is applied on an object initially at rest. Ignoring the friction, if the force is applied for a certain period of time and then the object is released how can its motion be described throughout? I also tell June that the force-time graph for this question is a constant force in the first half and a zero force in the second half.

FT: How would you describe its velocity?
June: It's gonna increase here, I hope [pause] umm, if you are applying this constant force I think it is gonna increase.
FT: What kind of an increase? A decreasing increase, increasing increase, or steady increase?
June: Increasing increase.
FT: Umm, like the one in 11, I guess, right?
June: Yeah.
FT: Increasing increase. Why would it be an increasing increase?
June: Because you are applying the same force and.. if from like right here it starts, the velocity starts increasing as you keep applying that same force that’s just gonna keep increasing keep increasing keep increasing.
(Interview Excerpt 3.34, March 3, 2000, lines 540-550)

June interprets a "continuous increase" as an increasing increase even though Newton’s second law says a constant net force on an object increases its velocity at a constant rate. June gives as an example that if an object starts motion from at rest, then the
velocity would increase by 5, and by 6, and so on (in an increasing manner) in equal time intervals. However, she indicates that she is not sure if this is going to be the case and explains her source of confusion:

June: I am thinking about when something falls. I guess [pause] it increases at a constant rate.
FT: And the reason is?
June: Because gravity is a constant but increasing at a constant rate makes it build speed.
FT: Speed will go up each time you mean?
June: Yes.

(Interview Excerpt 3.35, March 3, 2000, lines 565-569)

As it was previously pointed out June had the notion of acceleration as a level of speed. According to such an understanding, objects moving with higher speed have more acceleration. This notion originates from the idea that the greater the force the greater the speed, i.e., drawing a linear proportional relationship between force and velocity. Thus, in such a scheme "change" in speed does not exist as it does in the Newtonian sense of acceleration. Instead there exist discrete levels of speed, which are attained by forces proportional to them.

At this point June is attempting to match free fall and motion on a horizontal line due to a net constant force. But, there are many counter everyday experiences in her mind that make such a transition difficult. The major difficulty is brought about by the fact that friction cannot be eliminated in real life. Questions stating that "friction is ignored" do not make sense to her as they do to an expert. I ask June to describe the velocity-time graph of an object if, during motion, there is a constant net force in the first half and no force in the second half as described above:

FT: So the graph will be like?
June: [pause] tsk tsk tsk
FT: The velocity-time graph.
June: [long pause]
FT: What are you thinking?
June: I am trying to remember seventh grade physical science [laughs] because I can remember talking about [pause] at a constant [pause] I'm really confused.
FT: What confuses you?
June: [pause] Whether it is increasing at an increasing rate or increasing at a decreasing rate or increasing at a constant rate? [both laugh] I am not even sure it increases so to say that it to try and figure out which way it increases.. I don't know I guess made me feel overwhelmed.
FT: Umm, do you wanna just leave it? And continue with this.
June: Okay.
FT: And for 11 you would say
June: [long pause]
FT: What are you thinking?
June: I am just going back to the original graph to make sure that I understand what's occurring. [pause] Thinking that "the magnitude of a force changes in time" [pause] So the force is constantly decreasing [long pause] which makes me wonder if you're pushing it, like once you get it rolling that first time, your second push need to be like can it be less to keep it moving at the same rate?

(Interview Excerpt 3.36, March 3, 2000, lines 570-590)

The example June just gave is an accurate description of what actually happens. For example, if a heavy cylindrical object is rolled on the floor (a smooth surface) it is the hardest to get it moving the first time but after it starts moving, smaller pushes will keep it moving at the same rate. The reason is a high initial speed requires high acceleration (a big change in velocity) and, as a result, a stronger push (big force). Since there exists friction between the cylinder and the floor, if the cylinder is released after the first push, its speed will be reduced at a constant rate. Counter-acting friction and keep the cylinder moving at a constant speed (equal to its initial speed) will only require, by Newton’s first law, a force equal to the force of friction, which is small.

However, June does not "see" the world through Newton’s laws. Her theory is that on rough surfaces (or where there exists a high friction), the force is proportional to velocity (e.g. like pulling a big chunk of a log in the woods), but if the surfaces are smoother, then only a big force is needed to start motion, and successive small pushes will keep it rolling at the same rate (e.g. pushing a cart on a vinyl floor). It is also noteworthy that June does not
experience the same difficulties in the cases of "outer space" and 'free fall" where eliminating friction from the picture is a lot easier. I am now compelled to remind June that in the above discussion friction is assumed negligible:

FT: Don't forget this is a frictionless surface and you said when you once you push something on a frictionless surface it will go on forever.
June: mm hmm.
FT: So, let's say you pushed something on a frictionless surface like ice. I mean ice is not a good example but this is the best..
June: [jumps in] It's gonna
FT: we can..
June: increase at a decreasing rate. Is that right?
FT: Say that again.
June: [enunciates] It's gonna increase at a decreasing rate.
FT: Is that [statement] 10?
June: Yeah.
FT: It is like you push something like in outer space
June: mm hmm
FT: and it goes with a certain speed and then you come after like 5 minutes and push it again
June: Yeah.
FT: What is gonna happen?
June: It's gonna.. it's gonna increase. But you are not pushing it as hard. So, I am gonna say this is false. That 11 is false. I am gonna stick with 10 being true even though it might contradict what's up here. [laughs]

(Interview Excerpt 3.37, March 3, 2000, lines 591-610)

At this point June demonstrated an understanding of force and motion as Newton's second law suggests. But that is not the whole story. A complete understanding of motion is only possible through Newton's first and second laws together.

4.3.1.3.9 Newton’s first law vs. force implies motion

June has always associated presence of force with motion and lack of force with no motion. According to her motion always needs to be in the direction of the applied force regardless of initial conditions. This shows a deficiency in understanding Newton’s first law, which surfaced again when she responded to statement 12:
June: [reads statement 12] "The object's velocity will decrease at an increasing rate, and then motion will be reversed." No, I don't agree with that. I don't think the velocity is gonna decrease because it's just gonna keep going because it is frictionless.

FT: Okay. But that contradicts what you said before. [laughs]

June: That it would stop?

FT: mm hmm.

June: [taps on the table with her fingers]

FT: Do you still think it will stop at t 2?

June: I think if you stop it, it will stop.

FT: If you don't push it anymore, if you just hold back?

June: No, if you just hold back it's gonna keep going. But if you, if on this final push if you push and then you quickly run around to the other side and start pushing back this way, I don't know is there a split second there where while it is reversing directions that it is going is there a stand still?

FT: Oh, I know what you mean. Like umm..

June: Like if I were running pushing this

FT: Okay

June: and then turned quick instead of pushing it this way will there that flash second where it stopped dead as it would switching..

FT: So, at t 2 the object will start moving in the opposite direction is that what you are thinking?

June: Yeah.

FT: Okay.

June: Is that.. am I not thinking of it right or?

FT: Let me get this straight like you are saying in the first half of the motion the object builds up speed with a decreasing rate, is that what the 10 says?

June: Yes, yes!

FT: And then at t 2 it will stop because you will go around at the other opposite of the

June: Yeah

FT: side of the object

June: Reverse

FT: and start pushing in the opposite direction so the object will at that moment momentarily stop and start moving in the other direction.

June: Yeah.

FT: Okay.

June: Yeah. But you are actually already applying the other force so if its gonna like if there is a second where it stops it's like a split second because you are applying the force in the other direction again.

FT: I see.

(Interview Excerpt 3.38, March 3, 2000, lines 612-649)

I direct June's attention to the fact that in the question in which the applied force vanishes and slowly starts getting bigger in the other direction at t₂, at that point the object has already developed a high speed, which she agrees with. This helps June re-consider her answer and reveals how she has been automatically associating change of direction of force with change of direction of motion:
FT: This question for example, if something is coming onto you real fast
June: mm hmm
FT: Okay? And you are fixed at this point.
June: mm hmm.
FT: And you wanna oppose its motion, okay it is coming to you real fast. So, can you just stop it
June: No
FT: or
June: No, It's gonna push you in the other.. unless you apply
FT: Real hard.
June: real hard like if you can out due the force that's coming at you with which if you said it is coming real fast you probably can't.
FT: So how do you think it will happen here? So when the motion reverses the initial force you apply is very small and it increases you know in the other direction moment by moment so the first push in the opposite direction is not that hard.
June: No.
FT: So, what will that do to the object?
June: It's probably just gonna slow it down like it'll still be moving the original way that it was but your force is just gonna slow it slow it slow it until it realize or until it gets to a point where your fo.. your increasing force starts it in the other direction. Did I answer the question?
FT: Are you saying like until one such point, there'll be one such point, that the velocity will decrease, decrease, decrease and then since you are applying an increasing force the object will stop and move in the other direction?
June: hmm
FT: Is that what you are saying?
June: Yeah.
FT: Okay. I am just trying to understand what you are saying.
June: Yeah. That's what I am saying. I guess what here when you said the direction of the force is changed instantaneously, it just says the direction of the force it doesn't say the object has changed instantaneously.
FT: mm hmm. So was it your initial understanding that the object's movement changed?
June: Yeah. That was my like in reading through I thought "well it is gonna stop on a die in here and turn the other way." But that's not gonna happen.

(Interview Excerpt 3.39, March 3, 2000, lines 653-684)

4.3.1.3.10 Acceleration revisited

June now thinks that speed will increase in the first half of the motion and then start decreasing since an opposing force is being applied in the reverse direction starting at \( t_2 \). The question becomes how she relates the concept of acceleration to such a motion. Statements 13-15 are about the nature of change in acceleration according to the graph in question.
June immediately reacts to statement 13 by stating that acceleration should be increasing. This is consistent with the idea that speed is proportional to force and acceleration indicates how fast an object is moving (i.e. the level of speed). She then remembers (through the outer space idea) that in a frictionless environment if an object is pushed and released it will continue to move with a certain constant speed. Thus, June concludes that the acceleration (the level of speed) should be constant. On the other hand, the force given in the question is diminishing in time. Once again she re-considers what she says and struggles to make sense out of all these ideas which are, for her, and sort of "floating in the air." Sorting out those ideas and reasoning according to them is the task June now faces:

FT:  Okay. So, let's move on.
June: [reads statement 13] "The object has a constant acceleration throughout its motion." [pause] I actually think it has an increasing acceleration.
FT:  Okay, why do you think so?
June: Oh, I see these next questions ask that [noting statements 14 and 15]. Umm, in thinking about the outer space idea the first push is gonna get it at a constant acceleration. Oooo wait a minute. Acceleration is the rate with which it speeds up. [long pause] So, here you are gonna be increasing the acceleration. Oop, wait a minute. Tsk tsk tsk tsk tsk [laughs]. [pause] [writes on the graph, see the worksheet in Figure 4.21] small force, big force. Ooo, no a decreasing force right? Small force both here at the center.
FT:  You mean on the two sides of the center?
June: Yes! And big up here. Okay. [pause] It's moving, it's moving, it's moving, but you're decreasing your force you are applying to it. But you are still increasing its movement. And here [pause] very small at first [pause].
FT:  The force is very small at first yeah.
June: Yes. [pause] I am actually reading over 14 and 15 to decide because they all relate to the same thing, so.
FT:  They cannot all be true at the same time, huh?
June: Right. [pause]

(Interview Excerpt 3.40, March 3, 2000, lines 685-703)
June has some information out of which she is trying to make sense. She faces new ideas, examples, and conflicts. Before going any further, I want to probe her current ideas about acceleration and how she relates them to force.

**FT:** How do you go from force to acceleration? I mean conceptually what does that tell you?

**June:** Umm [pause] well [pause] something that's in motion if I just give it a little shove its acceleration would be [short pause] smaller than if I give it a huge shove. Because the [murmuring] so the way I see it I guess is that the force applied to something already in motion the greater the force applied the greater the object is gonna accelerate.

**FT:** Okay.

(Interview Excerpt 3.41, March 3, 2000, lines 704-709)

This statement, namely the greater the push (force) the greater the acceleration, is consistent with the Newtonian definition of acceleration. However, a crucial determination is
in what sense June uses the word acceleration. Keeping in mind that June uses acceleration in a way closer to 'speed' than 'change in speed' is important in understanding what she really means by "the greater the force applied the greater the object is gonna accelerate."

June: [long pause] So I guess what I am saying is that I feel like once eventually, like probably.. I don't know somewhere down.. down in the lower part of..

FT: The second half [pointing to the graph]

June: ..yeah the second half, past t 2 aways, once you finally get the thing going in the opposite direction you are gonna keep at.. like adding larger and larger force so I think you're really gonna be increasing its acceleration once you get down here towards t 4. Because it is sort of in like constant motion anyway and you are increasing the force you are adding, so it is gonna be going more rapidly. But this one like even if.. if I just pushed it once it would like flow using the outer space idea it would flow like all the way down no matter what. But I am still giving it like tiny pushes so my pushes are accelerating it but it is not accelerating greatly. So, I guess what I wanna say is increasing acceleration here but at a decreasing rate, and then increasing acceleration at an increasing rate.

(Interview Excerpt 3.42, March 3, 2000, lines 710-721)

Although just minutes ago June demonstrated an understanding with a correct reasoning that an object under the influence of a force given in the question does not stop at t_2 and that the reversed force acts to slow down the object rather than instantaneously stopping it and reversing its direction of motion, she now goes back to her original conception that motion shall be in the direction of applied net force. Previously June had described how it is more difficult to get things to move the first time and how it gets easier after that. June now refers to "an object already in motion" and how it is easier to get it moving more rapidly especially when a greater force is applied. What she means is if an object already has an initial speed on a smooth surface, then successive little forces will get it moving only a little faster, but bigger forces will get it moving much more faster. At the end of the above excerpt, June described the acceleration of the object throughout its motion as "increasing acceleration here but at a decreasing rate, and then increasing acceleration at an increasing rate" (see Figure 4.22 below).
Figure 4.22. A sketch of variation of acceleration in time constructed according to June's description of "increasing acceleration here but at a decreasing rate, and then increasing acceleration at an increasing rate."

What June thinks can be interpreted in this way: the object will start its motion under the influence of a decreasing force. Although she originally thought that magnitudes of force and speed would be proportional, June now uses the outer space idea in order to imagine 'frictionlessness' and thinks that every additional push should add up to the object's existing speed according to its strength. During the first half of the motion the pushes are getting weaker each time, so the velocity should increase at a slower rate. In the second half of the motion the direction is reversed, but this time the force is increasing therefore the velocity should increase as well. Since acceleration shows how fast an object is going, it also gets bigger and bigger during motion in the second half (resembling exponential like growth). Hence, velocity and acceleration are paralleled in June's description for this motion. It is also noteworthy that June mentions rate of change of acceleration as a function of force, which is not defined in Newtonian mechanics. Newton’s second law states that force and acceleration are proportional and the constant of proportionality is the mass of the object undergoing acceleration (F = ma). But June's description makes sense since she is not referring to the
Newtonian concept of acceleration when she uses the word. She is indeed referring to the level of speed or fastness when she uses acceleration!

There is an obvious similarity between June’s description of acceleration for this motion and statement 10, which is "The object’s velocity will increase at a decreasing rate, and then will decrease at an increasing rate." The second part of the statement is different than June’s because she thinks that the direction of motion is reversed at $t_2$ where velocity starts increasing from zero. In sum, June now can make a connection between force and speed in a frictionless environment. Additionally, she can articulate how speed changes according to an applied force by stating that not the magnitude of speed but the change in speed is proportional to force (Newton’s second law). She is still confused, however with Newton’s first law and appropriate usage of the terms velocity and acceleration. The meaning June gives to the term acceleration, notwithstanding her contact with the scientific definition of the concept several times (including during this interview session), and the struggle she goes through attempting to making sense of Newton’s second law suggests that she may not have any sense of the concept of acceleration. It is highly probable that the physical meaning of acceleration does not exist for her. Thus, I want June to repeat her last statement in order to make sure I understand her correctly and it is not a slip of the tongue that she uses acceleration in the same manner as speed.

FT: Say that again.

June: [writes on the worksheet, see Figure 4.21 above] Increasing acceleration at a decreasing rate, increasing acceleration at an increasing rate.

FT: Okay. You mean when you apply bigger force the change in the acceleration gets bigger? [long pause]

June: Yeah, like my little pushes are still gonna increase the first.. it in the first half they are gonna keep increasing it. But it’s not like I am applying less and less force so although the acceleration is gonna keep oooh so wait a minute does that stop? Tsk tsk [pause]

(Interview Excerpt 3.43, March 3, 2000, lines 722-729)
June means to say that although in the first half of the motion the pushes are constantly weakening, they still increase the speed (she uses the word acceleration in place of speed). Since, in her original thinking, less constant force meant less constant speed she points out that this is different. At this point she remembers that she concluded before that the object does not stop at $t_2$, and this creates confusion for her. I feel it is best if she can explicitly articulate what she understands as the relationship between force, motion and speed, in order to be able to explicate her own reasoning.

FT: What is the relationship?
June: Acceleration is an increase in speed. Is that correct or?
FT: Say that again.
June: Acceleration is an increase in speed. An increase in the rate of [pause]
FT: Speed?
June: Yeah.
FT: I was gonna ask that. What is the relationship between speed and acceleration and what is the relationship between force and acceleration?
June: [long pause] Because there comes a point here I think where in the first half when you are pushing it and [pause] it’s probably [long pause]
FT: What are you thinking?
June: I am thinking that each successive push whether it is small or big keeps like the thing is moving you know what I mean. So like pushing it real hard it's gonna move that same rate the whole time. But then later giving it like not so hard of a push it's gonna be moving.. it was already moving.. it's moving.. a little faster now but then giving it like a little less of a push.. because the sec.. like the second time you push it, it starts moving at that rate.
FT: hmm mm.
June: So then the third time you push it even though you're pushing it less it was moving at the second rate. So that you are increasing it again in a way. Do you see what I mean?
FT: hmm mm.
June: So, I am a little confused as to whether that’s the same thing as increasing your pushes like harder harder.. because [pause]

(Interview Excerpt 3.44, March 3, 2000, lines 730-753)

June’s definition of acceleration is peculiar – increase implies a change. If the initial speed is $s$ and it is increased by $\Delta s$ then, according to above definition, $\Delta s$ is the acceleration. Therefore, the greater the $\Delta s$ (change in the speed of an object), the greater the acceleration will be. In other words, if two objects start moving from rest and one gains more speed than the other, it would have a greater acceleration at that moment. Hence, any faster object, even
if it has a constant speed at the time, maintains a greater acceleration than others (i.e., if a car on a two lane road passes a slower going car, then it has more acceleration even if they both have constant speed). This explanation is consistent with my earlier interpretation that according to June acceleration implies *fastness*, and it ignores the definition of acceleration as \( a = \frac{\Delta s}{\Delta t} \), which is the change in speed per unit time.

In the above excerpt June shows how she now understands motion in a frictionless environment, just like she showed little while ago. She mentions objects maintaining their speed after a push and describes the effect of applying a push on an object already in motion as an increase in speed. Additionally, June describes the results of applying a "hard push" and a "less push" instantaneously as being proportional to an increase in speed. Thus, June concludes that every additional push on an object, irrespective of its magnitude, will give rise to the final speed. This is a positive gain in June's learning about force and motion in a frictionless environment. On the other hand, there are indications (see June's last sentence above) that she still maintains her original conception that an object’s speed is proportional to the magnitude of applied force. Since these two conceptions cannot be true at the same time, June gets confused. After these discussions I want June to decide between given statements for acceleration in the worksheet:

- **FT:** [smiles] Okay. um if you quickly decide between the last three what would you say? What does your instinct tell you? [pause] Is thirteen true or false?
  - **June:** [writes]
  - **FT:** [reads what June wrote] False.
  - **June:** This one seems closest to what I think.
  - **FT:** Okay.
  - **June:** Fourteen. But I don't know.

*(Interview Excerpt 3.45, March 3, 2000, lines 754-758)*

From the beginning of this discussion about acceleration June has stated that she expects an increasing acceleration for the motion described by the given force. Obviously
she cannot find among statements 13, 14, and 15 a choice acceptable for her. Although at last June picks the right choice (statement 14), her reason for her selection can be best understood in light of the sketch above (see Figure 4.22). June sees that fastness of the object in question is not increasing significantly as time approaches \( t_2 \) whereas it is increases tremendously as time approaches \( t_4 \).

A correct statement from June's perspective, as she declared above, would be "increasing acceleration here but at a decreasing rate [in the first half], and then increasing acceleration at an increasing rate [in the second half]." In contrast, an expert would think and reason according to Newton's second law as follows: "acceleration is the rate of change of speed, which is proportional to the applied net force on an object and an object accelerates as long as there is a net force on it. Hence, the shape of the acceleration-time graph must resemble the force-time graph: whenever there is a change in force, there must be a corresponding change in acceleration factored by the mass of the object in motion \( (a = F/m) \). For the given force-time graph, the acceleration-time graph needs to be drawn as a constant decrease in the first half of the motion and a constant increase in the second half of the motion in the same direction as force."

4.3.1.3.11 Understanding change at varying rate through June's population analogy

At this point, after finishing discussion on all fifteen statements provided in the worksheet, I wish to probe further how June has been thinking about force and motion. Remembering that she created an analogy earlier (see excerpt 2.7) to make sense of the
effect of force on moving objects and to integrate acceleration into the picture, I now wonder if June had considered it during this session:

FT: Um when we talked about this before you gave the population example, do you remember? If the increase in population, the rate of increase in population decreases what will happen?

June: Yeah the population is still increasing but at a decreasing rate.

FT: Yeah. That was what we talked about before. Remember that?

June: Yeah. I thought, I thought of that whenever I said it but I didn't...

FT: Today?

June: Today... yeah like rrr... that's... that's the first time I came in contact with like something increasing at a decreasing rate like I've never discussed it before. So the first experience I had with was population and the fact that although like a country's population can totally be continuously increasing, increasing, increasing but it can increase at a [short pause] at a varying rate.

(Interview Excerpt 3.46, March 3, 2000, lines 759-770)

One of the main stumbling blocks for June has been making sense of acceleration as rate of change (see excerpt 1.13). Although on many occasions has she repeated this definition, it was obviously just a figure of speech, not due to meaningful learning. From the excerpt above it is understood that June has always thought of change in quantity as a steady process. Therefore, if speed is changing and this change is brought about as a result of an applied force, then, that speed must be proportional to the magnitude of the applied force. This line of reasoning totally eliminates acceleration from the picture. Accordingly, rather than acceleration, speed becomes proportional to applied force. It is essential to understand force as an agent which causes change in speed only as long as it is applied (Newton's second law). However, June think is that change in speed is caused by change in force \( \Delta F \propto \Delta \dot{s} \), and the stronger the applied net force the higher the speed \( F \propto \dot{s} \). For her, increasing (a positive change) net force on an object creates an increase in speed, and she calls this process "acceleration." Consequently, it becomes odd to think that any net force can produce an increase in speed.
It is amazing that even after one year June still remembers vividly the population analogy she created to explain how she came to understand the effect of force on speed. But, although June can now make sense of a quantity changing at a varying rate, she is having difficulty extrapolating that analogy to force and motion. I take on the task of helping June make the connection between the population analogy and motion:

FT: Okay. So, if this is like, instead of force, population increase rate, okay, what would you say? The rate, the population will increase or decrease? This is the rate of population and this is time. Rate of increase of population instead of force. Write that down 'rate of increase of population' is the vertical axis and the horizontal axis is again 'time' [see Figure 4.21]. So, what will happen to population? At t 2 will it vanish?

June: You mean well it like...
FT: There'll be nobody.
June: No! that's not... that's not what happens.
FT: So, when will be the number of people be maximum?
June: [long pause] Rate in increase in population. So, no matter what, it is an increase.
FT: Okay.
June: It's just increasing by less and less. So, like the first time it increased by ten and then nine so forth, right?
FT: hmm mm.
June: Where is it the biggest? It is the biggest right here.
FT: t2?
June: Yeah.

(Interview Excerpt 3.47, March 3, 2000, lines 771-801)

In this way, understanding that a positive rate of change gives rise to the total quantity "no matter what" helps June infer correctly that, according to the rate of change graph given in Figure 4.16, the quantity in question should reach its maximum mid way through, quite contrary to her intuition since at that point rate of change becomes zero (applied net force vanishes).

In order to give a clearer description of how speed can increase when force decreases I provide June with an explanation of how the population analogy corresponds to force and motion terminology. After listening carefully and processing the information provided, June
is now able to make a transition from the population analogy to the object's motion and describe the change in speed as characterized:

FT: So, we can make the analogy like the "population" will be "velocity" and "rate of increase" will be "force." So, you know what I mean?
June: I am processing! [pause]
FT: Population will be velocity and rate of increase or decrease will be the force. Rate of decrease will be the negative force in the opposite direction.
June: [writes] Population equals velocity. Is that what you said?
FT: Not equals but analogous to.
June: Yeah, yeah okay. But and then you said?
FT: Rate of increase or decrease will be the force.
[June writes on the worksheet, see Figure 4.21 above]
FT: Positive force or negative force. [pause] So, when you give it a push each and every time although it is smaller the population will increase at a decreasing rate.
June: [pause] Okay. Population, the rate of population increase has its highest value right here, we are talking about the increase value.
FT: mm hmm.
June: At t sub 2 it is zero it is not increasing at all.
FT: mm hmm.
June: Has the same value as up here, down here so it's decreasing by the same amount here as it's increasing here.
FT: Yep.
June: And population equals velocity. So, the velocity is increasing like crazy up here, and then just increasing a little. And then..
FT: mm hmm when you get closer to t 2.
June: Yeah. And then at t 2 it's not doing anything?
FT: At that moment.
June: [repeats to confirm] at that moment. And then it starts decreasing..
FT: Each time with a greater rate.

(Interview Excerpt 3.48, March 3, 2000, lines 802-828)

4.3.1.3.12. Velocity and acceleration: What is the distinction?

Acceleration has been the focus of conversation during the second half of this interview session. June has been struggling to conceptualize how acceleration fits in the picture with force and velocity. By taking the rate of change in June's population analogy as the starting point, a transition to acceleration resulting from a net force on an object has been sought.
June recognizes that the greater gap, the distance between the line and the horizontal axis in the force-time graph, corresponds to a greater change in speed. However, she again tends to associate, the greater force with greater speed rather than greater change in speed. My efforts in the other direction, namely associating change in speed with acceleration, confuse June.

June:  So, actually I should be drawing this stuff here when I say it, right? Because this shows a greater rate that like because here will show a greater rate. But that's not what we [murmuring] is that..

FT:   I mean the rate is between the t and the graph
June:  Yeah
FT:   the line, yeah. [pause] So is that mm
June:  I don't know, because what's acceleration? [laughs] If the acceleration is like the velocity then I'd say it was..[pause]

(Excerpt 3.49, March 3, 2000, lines 829-836)

It seems that grasping the meanings of both the formula and the law is presenting great challenges for June in terms of applying them to everyday experiences. After all these discussions, I once again direct June's attention to the formulaic description of Newton's second law, \( F = ma \). I aim to describe algebraically the relationship between force and acceleration, considering the definition of acceleration and assuming that the formula holds true.

FT:   Do you remember the formula \( F \) equals \( ma \)?
June:  Yeah! That's the one I remembered [laughs].
FT:   Okay. It is the same object all the time, so mass is the same. So, if you increase \( F \) continuously the only thing can increase on the other side is..

June:  Acceleration!
FT:   ..acceleration. So, if you increase one you increase the other. So, um \( F \) is mass times acceleration but acceleration is the rate of change of velocity.
June:  hmm yeah.
FT:   Okay. So we can say that acceleration is the speed of speed. How fast it is speeding up, or changing..
June:  Okay.
FT:   ..increasing or decreasing.

(Excerpt 3.50, March 3, 2000, lines 837-848)
After finishing up all fifteen 'true/false' questions and having considered each of them together at length with June, I wonder how she would now respond to them to see if she gained any conceptual understanding during the interview. In her responses June begins to accommodate the population analogy while thinking and reasoning about force and motion in a naïve way:

FT: Um, do you wanna change any of the others, the previous ones? Now, real quick. You can put your new answers next to the previous ones.

June: Oh, okay. [Silently reads through the statements.] Well, if velocity equals population I am not sure then it has its greatest, its maximum values there. It has its maximum value here. [She points out to statements 2 and 3 and indicates that statement 2 is false and statement 3 is true.]

FT: Okay, so that will be. What about the first question? [asking her to go one by one]

June: [Reads statement 1] "Force becomes zero velocity will be zero, too." No, population is not gonna be zero.

FT: Okay.

June: [Reads statement 3] "At t sub 2 velocity will have its maximum value." True.

FT: Okay.

June: [Reads statement 4] "At t sub 2 the object's direction of movement will be reversed." True. Because it is increasing here and then decreasing here. Is that..?

FT: Okay, if that's what you are saying. Remember what we talked about if an object is coming your way real fast you'll be able to change its direction momentarily by applying a very small force?

June: No, but like we went from increase to decrease right here though.

FT: mm hmm. Oh, in that sense.

June: Yeah in the population sense.

FT: The population will start decreasing.. after t 2. [pause] If population is velocity, velocity will start decreasing?

June: Yeah.

FT: Does that mean you change your direction of motion?

June: No! [laughs] It doesn't! [laughs] No.

FT: Okay.

June: And that's the same thing I said up here when I said that. [both laugh] Isn't it? It's [reads the question from the worksheet] "direction of force is changed instantaneously" not its.. [emphasizes] the direction of force. Force is the key word right there "force" not "the direction of the object is changed instantaneously."

(Interview Excerpt 3.51, March 3, 2000, lines 848-874)

A weakness of June's population analogy surfaces: although force, acceleration, velocity, and displacement are all vectors, population is not. Therefore, change in direction
cannot be complimented by the analogy. June tries to remedy this difficulty by substituting transition from a continual increase to a decrease in place of directional reversal, but, obviously, such a substitution cannot cover the whole meaning of directional reversal. Additionally, June thinks that motion is always in the direction of applied force, which means that if the direction of applied force is reversed then the direction of movement should be as well. In the excerpt above it is also revealed that June almost automatically associates changing direction of force with changing direction of movement, and she finally realizes that preconception of hers, too.

June continues to think in terms of the population analogy while she responds to 'true/false' questions. The main difficulty seems to be, as also revealed in excerpt 3.48 above, matching the types of 'actions' taking place in both circumstances. Besides finding what corresponds to direction, she now runs into the problem of what 'stopping' means in the population analogy. She reluctantly answers that "population remains constant."

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FT: Okay. So, what does 5 say?
June: [Reads statement 5] "At t sub 2 the object will stop momentarily." Well, population is not gonna stop. But it is it gonna stop increasing and stop decreasing or just gonna be like a dead point there or nothing. No, that can't happen, can it? Can it be constant. I have no idea! Ighh! [reads again] "The object will stop momentarily" No! It is not gonna stop!

FT: The object will stop means?
June: It is not gonna stop! It means that it would
FT: ..the velocity
June: ..you like ice [471] like this and stopped it immediately.
FT: The velocity will be if it stops?
June: Zero.
FT: So, it is again like the first question, right?
June: Yeah.
(Interview Excerpt 3.52, March 3, 2000, lines 875-887)

Another term on which June gets confused is 'displacement.' What corresponds to displacement in the analog system (the population analogy) is not clear to her. Although velocity was identified as population before, the analog for displacement is still open ended.
In fact there is not any such corresponding term in the analog system for displacement; it has to be inferred from the meaning of velocity and its relationship to displacement. Thinking that such an analog automatically would exist in the population example drags June into confusion.

June: [Reads statement 6] "At t sub 4 the object will be at the point where it started its motion." No. [pause] Because the population started here.

FT: Okay.

June: [pause] And it was increasing.

FT: Population is analogous to velocity, right?

June: Here.

FT: But

June: Object

FT: It is not displacement. So if you go back to where you start you actually need to change the direction of your motion. [pause] What are you thinking? [pause] The question is ‘does the object ever change the direction of its motion?'

June: No.

FT: So, can it be where it started?

June: [nodes] igh igh.

FT: But since the population is analogous to velocity, what can you say about velocity at t sub zero and t sub 4?

June: Okay. So your question is?

FT: If you compare the velocity at t sub zero and t sub 4 will one be greater than the other or equal to each other?

June: This velocity will be greater than

FT: You mean t zero will be greater than t 4?

June: In the sense of population, yes.

FT: So the population

June: No.

FT: increased up until t 2 right?

June: Yeah.

FT: And then started decreasing.

June: Yeah but decreasing at the same rate here as it was increasing here.

FT: So?

June: They are the same.

FT: They will be equal? The population?

June: The population won't be equal.

FT: At t sub zero and t sub 4?

June: Yeah.

FT: But.. Tell me what you are thinking. I am confused now.

June: [makes a perplexed sound] igh!

(Interview Excerpt 3.53, March 3, 2000, lines 887-922)

In order to clarify what and how June thinks, I give a concrete example and, instead of imagining the situation purely qualitatively, ask June to use numbers. This time June successfully solves the problem, but she is still not sure she understands everything fully.
FT:  Like let's start, let's say there are a 100 people in a village at t sub zero okay. And tell me what is gonna be the number of people at t 2 and and what is going to be the number of people at t 4.
June:  [pause] a 100 people here.
FT:  mm hmm.
June:  And the population is gonna keep increasing but it is gonna increase at a decreasing rate.
FT:  Okay.
June:  So I don't know increased by 5 and then by 2.
FT:  Okay. So at t 2 will it be the minimum or the maximum or will it be zero?
June:  At t 2 it'll be the maximum, the maximum population. So I don't know let's say one ten. And then from t 2 to t 4 it's gonna be decreasing and the first year it is gonna decrease by a little so it'll be like I don't know one o eight, and then it is gonna decrease by more so it's gonna be one o four. And it is just gonna keep decreasing. But it'll be whatever it'll be the 100 at this point again.
FT:  Okay. So if the velocity is analogous to population?
June:  [sighs] Then the velocities will be equal at t zero and t 4. Which is really confusing but the analogy is helping.
FT:  Okay. So starting to make sense.
June:  Starting. I am not sure though like if you give me this blank sheet I think I'd be lost again.
FT:  If you wanted to do this from scratch again?
June:  Yeah. I'd be like..
FT:  So you won't know where to begin?
June:  [both laugh] Well, I'd know sort of where to begin, if I can remember this analogy I'd be okay.

(Interview Excerpt 3.54, March 3, 2000, lines 923-945)

An important corollary of this excerpt is that if a person is using an analogy while reasoning about a case, June's case exemplifies that one does not always need to understand all the concepts and relationships entirely. Instead, if one understands the analog system, all she needs is to obtain a correspondence table so she can see what happens in the target system.

FT:  Okay, [points to the worksheet statement] So, seven.
June:  [Reads statement 7] "At t 4 the object will be at the farthest point with respect to where it began its motion." No.
FT:  Why do you say "no"?
June:  Because it is at the same point where it began its motion.
FT:  Remember the velocities are the same at t sub zero and t 4. So..
June:  Oh! Yes!
FT:  So does it ever reverse its direction of motion?
June:  No! It doesn't it just keeps going in the same direction.
FT:  Just keeps going yeah.
June:  So, [refers to statement 7] that's true.
FT:  Eight?
June:  [Reads statement 8] "Right at t sub zero the velocity will reach its maximum" [pause] yes! and oop "and from then on it will gradually decrease."
June's second round of re-considered responses show that her understanding of force and motion is still immature after this ninety-minute session. Like a pendulum, she goes back and forth between her own conceptions and the bits and pieces of information presented to her. June admits that going over these very same questions from the beginning would present her a real challenge. Whenever she responds quickly she reveals her preconceptions, not showing a hint that she is using the learned knowledge. It is amazing to see how persistent June's preconceptions and intuitive responses are.
4.3.2 March 31, 2000: Administering the Force and Motion Conceptual Evaluation (FMCE)

On March 31, 2000 June was given the FMCE test (Thornton & Sokoloff, 1998). In the original instrument questions 1, 3, 4, 7, 16, 18, and 19 ended with the words "constant acceleration" in parenthesis which described speed changing at "a steady rate." Since my purpose was to probe June's understanding of the relationship between force and velocity, I wanted June to make any association to acceleration on her own without having it prompted. Therefore, in the version of this instrument given to June, these words were deleted (see Appendix B for the FMCE test and June’s answers). Before June began answering questions I told her that this is a follow up of the previous interviews and that she should read the questions very carefully. I also emphasized that whenever she feels she does not understand a question fully she could ask me. An interpretation and analysis of June's answers are provided below.

4.3.2.1 The force of friction and pushing a sled on ice

June begins the test and reads the directions for answering the first seven questions. I make sure she understands the task completely. She responds to all seven questions without asking for any clarification.

June's responses to questions 1 and 4 indicate that she still associates 'speeding up at a steady rate' with increasing force in the direction of movement. On the other hand, she associates 'slowing down at a steady rate' with a constant force in the direction opposite to the movement (questions 3 and 7). Since both speeding up and slowing down at a steady rate
involve uniform acceleration, all four of these questions measure how someone understands Newton's second law, and June's answers imply that she does not 'see' these two cases being related to the same principle (Newton's second law). Her answer to the sixth question about slowing down is in congruence with two similar questions (3 and 7). However, here, she misinterprets 'having an acceleration to the right' as 'the sled is moving to the right' and thinks that 'acceleration is in the direction of movement, not force.'

She responded in a contradictory way to movement with constant velocity questions (questions 2 and 5). While preferring 'constant force implies constant velocity' idea in the former, she chose 'constant velocity requires no force' idea in the latter. Somehow the wordings of these questions must have made a difference and conveyed different meanings for her.

After June finished all items in the FMCE test, she provided quick explanations to my questions about the sled problem. I was curious to know if she noted that friction should have been ignored while answering these questions. Her understanding of "ignoring friction" is:

**FT:** When it says "friction is so small that it can be ignored" what do you understand?
**June:** Um [pause] I understand that any.. any force that friction would [pause] any role that friction will play in the movement of whatever object we are talking about we're ignoring.
**FT:** Okay.
**June:** It's like.. like you said like pretending something is in outer space or like on its own.. when we were in class we said it on a really icy surface that we are pretending that it is not.. there is no friction between the object and the ice.
**FT:** So, when we are talking about ice and icy surface, a real icy surface, and when we say I push when we say there is no friction okay what will happen if I push an object like a hockey puck
**June:** right
**FT:** and you know just push it what will happen?
**June:** It's just gonna keep moving.
**FT:** Forever?
**June:** Sure.

(Interview Excerpt 4.1, March 31, 2000, lines 96-110)
These are wonderful explanations. It is also amazing that she remembers almost verbatim how frictionlessness was explained more than a year ago during the small group instruction. What becomes more interesting is her explanation for the first question in FMCE which comes right after the discussion above:

**June:** Um [pause] I thought it was A for first one because we wanna keep the sled moving toward the right and speeding up at a steady rate.

**FT:** mm hmm.

**June:** And otherwise I think if we don’t keep increasing the strength of the force that it’s just gonna stay at a constant rate.

*(Interview Excerpt 4.2, March 31, 2000, lines 113-117)*

Therefore, it is evident that her answers were intentional and not given by mistake. This excerpt also solves the problem in interpreting her contradictory answers for questions 2 and 5, revealing that June still thinks a constant force (push) is needed to maintain a constant velocity (see also her answers to pre-test and post-test questions in sections 4.2.1 and 4.2.5 respectively).

4.3.2.2 A toy car on a ramp

In the second part (questions 8-10) a toy car moving on an inclined plane is presented. It is given a quick push and then released causing it to roll up, reach the top of the inclined plane and come back again. According to June while moving up there is a net decreasing force on the toy car; at the highest point of the ramp the net force is constant; and while the toy car is moving downward the net force is increasing. This is consistent with her pre-instructional ideas except for the presence of a constant net force at the top (see the description of instruction and discussions in day 3 of case study group teaching in section
4.2.2.3). Why she thinks there should be such a force at the highest point is revealed during
her conversation with FT while she was attempting the questions:

**June:** Where this one.. whenever asks you about um the car at its highest point.
**FT:** What was that?
**June:** Um for number nine it asks you about the car at its highest point.
**FT:** mm hmm. What happens when the car is at the highest point?
**June:** Okay, now does that mean like when we're talking about the force here is that,
um, like the net force you apply to like to push it up or forces like force of
gravity?
**FT:** Both.
**June:** Both?
**FT:** Both, I guess.
**June:** Okay.
**FT:** What happens is you push and release, just one time push, and what will happen?
The car will go..
**June:** And then it's gonna..
**FT:** ..and then come back.

*(Interview Excerpt 4.3, March 31, 2000, lines 26-39)*

According to June's alternative framework of force and motion, the magnitude of
force is proportional to velocity and there should not be a force on an object if its velocity is
zero. On the other hand, she knows that gravity acts on objects at all times, so when she
reads question 9 these two bits of knowledge contradict each other and make it difficult for
June to conclude what the force would be at that point on the toy car.

Since the toy car problem was demonstrated and discussed during instruction I
wanted to know how June explained such situations. Upon my request she starts explaining
her answer to question 8:

**June:** I have G. And that decreasing force up the ramp.
**FT:** mm hmm.
**June:** Because at that point the car is moving up the ramp and I think that the
majority of the forces are acting on the car to move it up the ramp.
**FT:** Okay, when we read the question says "refer to a toy car which is given a quick push
so that it rolls up an inclined plane" okay. You just push and you don't keep in contact
with the car, okay. Just give it a push and then you are not touching the car anymore.
It is rolling up the ramp and then coming down, okay. So, if G which is "net
decreasing force up the ramp," I mean where does it get the force, the car, or why is
it decreasing?
**June:** It is decreasing because gravity is pulling down on it.
**FT:** Okay.
**June:** Or like, [short pause] yeah.
Alright, you think that gravity is always there, and pulling down the ramp?

Yes.

When the car is at the highest point what happens?

I think that is the point where the forces are constant down the ramp.

(I Interview Excerpt 4.4, March 31, 2000, lines 119-134)

Although June maintains the idea of the presence of the force of gravity at all times on the toy car, she also imparts a force to this moving object which again connotes the old impetus theory (see Figure 4.1 for June's answer to question 5 of the pre-test).

Tossing a coin up

June responded to questions about the forces on a coin tossed straight up in a similar way (questions 8-10) – force is in the direction of motion and decreases while the speed decreases and increases while the speed increases. However, at the highest point for both the toy car and the coin, where the speed is zero, she assumes a net constant force, though it was not an easy decision for her:

(taps on the table, as if something is puzzling her)

What's that?

Well, I remember talking about like when an object like when we tossed the ball up and when it reached its highest point there is something that happen. And I wouldn't think that it would be the forces will be zero. But [pause] because gravity is on it the whole time.

Gravity is on it the whole time?

Yeah. Like no matter where it is in its pass, so I guess [pause]

Which question are you talking about?

I was just, it was in reading this..

Oh the, okay, the bottom part.

Yeah. [very long pause] I think that was more.. it had to do with it's motion. And, not the forces acting on it.

Speaking about?

I think the like remembering something about the highest point of an object thrown up would be having to do with its motion and not the forces acting on it. Like its, like at its highest point its velocity is zero.

Which means if the velocity is zero [pause] it will stop. And then?

Yeah, and then it's gonna fall. Like it's gonna change directions. So, it's not necessarily that there is not a force acting on it, at that time. It's just.. [pause]

(I Interview Excerpt 4.5, March 31, 2000, lines 41-59)
Here, June modifies her alternative conception that 'no force' would require stopping. She makes a special case for objects moving under the influence of gravity (as opposed to perhaps motion on a horizontal line). Now her theory is adjusted to her observations.

After June completed answering all the items in the questionnaire, I pointed out the similarity of her answers between the 'toy car' and the 'coin toss' questions:

FT: Do you see any similarity between the first three and 8, 9, 10 and 11, 12, 13?  
June: Well, I have the same answers. So, yes.  
FT: Okay.  
June: [laughs]  
FT: Because of the reason.. why do you think they are sort of similar?  
June: Because it's talking about something.. an object's motion going up and then coming back down.  
FT: Okay. Does the gravity play any role in this similarity?  
June: Yes.  
FT: Present at both cases?  
June: Yes.  

(Interview Excerpt 4.6, March 31, 2000, lines 135-145)

The similarity of her answers to both toy car and coin toss questions indicates that at least her answers are consistent with one another and shows how she 'sees' motion against and in the direction of gravity.

4.3.2.4 Interlude

In the light of these data it can be concluded that June assumes that a force is imparted during the initial push to a moving object but the force gets reduced (or used up) during motion. The cause of the slow down during motion (e.g. upward movement of the toy car on the ramp) is the downward pull of the gravity. Therefore, to keep objects in motion with constant speed, a constant force is required which compensates for the dissipated amount during motion.
June's understanding of involvement of force in "toy car" and "coin toss" problems can be depicted as shown in Figures 4.23 and 4.24. Figure 4.23 shows how June envisions the net force on an object moving against gravity when tossed up. The discontinuity in the middle is what was puzzling her since she was not sure how to solve the problem of having a zero velocity without having a zero force. She concluded, "it's not necessarily that there is not a force acting on it, at that time" (see excerpt 4.5). Therefore, June reached a reconciliation between the two conflicting ideas.

However, if the force on an object which is continuously slowing down to a full stop and then speeding up was to show the same behavior as speed (the dotted line in Figure 4.25) when combined with the force of gravity (the dashed line in Figure 4.25), the resulting force (the solid line in Figure 4.25) would not make sense to June at all for the purposes of describing such a motion.
Figure 4.23. Variation of force on objects moving against gravity if pushed once and let go.

Figure 4.24. The constant downward force of gravity.

Figure 4.25. If the force imparted to an object continuously decreased and passed through the origin.
4.3.2.5 A toy car on a horizontal frictionless surface

The next set of questions (14-21) in the FMCE are concerned with the movement of a toy car along a horizontal line on a frictionless surface. June's answers indicate four things: movement is in the direction of the applied force; maintaining a constant velocity requires a constant force; speeding up requires an increasing force; and slowing down means a lessening of the net force on the toy car. All this can be summarized in one sentence: the greater the force the greater the velocity (see the dotted line in Figure 4.25).

4.3.2.6 Acceleration

Questions 22-26 are concerned about the acceleration of the toy car while moving along a straight line on a frictionless surface. June characterizes speeding up as increasing acceleration, constant velocity as constant acceleration, and slowing down as diminishing acceleration.

Similarly, questions 27-29 ask the relationship between acceleration and speed in the context of a coin tossed straight up into the air. June associated the upward movement of the coin with decreasing acceleration in that direction, and its downward movement with increasing acceleration. She also responded that at its highest point the coin would have no acceleration. As in the case of force and velocity, according to June, the more the acceleration the more the speed, and there is no acceleration if velocity is zero.
The similarity between June's responses to these two sets of questions and her answers to the post-test questions (see Figure 4.3) is remarkable; it demonstrates no change in her conceptions since then.

Questions 30-39 are about Newton's third law and momentum. Although June also answered these questions they will not be evaluated here.

4.3.2.7 Velocity

The last set of questions (40-43) is about interpreting velocity–time graphs of a car moving along a straight line. June related constant velocity with a horizontal line, steadily increasing velocity with constant slope, and reversing direction with shifting from positive to negative velocity. These answers indicate that she interpreted the velocity–time graphs appropriately.

4.3.2.8 A Remark: Nothing has changed!

The consistency in June's responses to questions 40-43 show that in the previous sets of questions (14-21 and 22-26), her non-Newtonian (Aristotelian like) answers can be attributed to a conceptual deviation rather than problems that might be associated with interpreting the graphs given with those questions. In fact, when her responses to the FMCE items are evaluated as a whole and compared to earlier results (e.g. see her answers to post-test and UVFQ), it can be seen that June's ideas about force and motion were amazingly stable during the course of the study despite my interventions.
4.3.3 April 12, 2000: A Follow-up interview

Upon evaluating June's responses to the FMCE test, I interviewed June once more to inquire about her responses directly. We met in less than two weeks after the last interview session on April 12, 2000. Since June had pointed out the similarity between population increase problems and force-velocity problems, I was very optimistic that this would help June understand the roles played by force and, hence, acceleration in explaining motion in the Newtonian sense. But the past two interviews had showed that there were no conceptual gains at all. In this follow-up interview, I wanted to ask June what she remembers about her population analogy and if she ever thought about it while answering the questionnaires in the last two interviews.

4.3.3.1 The population analogy translated to motion

When I ask June if she still remembers the population analogy, she starts talking about the axes and draws the graph in Figure 4.26. We then discuss which axis was used for what variable:

FT: This was a graph of?

June: It was the graph of a.. like umm.. the motion of an object if you were gonna change the force that you were.. I think you were gonna apply different force.. and I can remember having a big issue with thinking that it was gonna turn around when pushed the other way but..

FT: So, the vertical axis is force, shows force and the horizontal axis is

June: [jumps in] Time.

*(Interview Excerpt 5.1, April 12, 2000, lines 14-21)*
June reconstructs the graph given in UVFQ as she remembered it (see Figure 4.26).

Then, I ask her to recall the population analogy and what it tells her.

June: [pause] Tsk, it was the issue of something still increasing even though it wasn't increasing at an increasing rate.. like the population but the population doesn't just automatically become zero. The population could be [pause] because I remember I was thinking that the that.. the motion of the object at the point where the line crosses the time axis thinking that it would be zero and you said "is your population zero at that point" and I said "no" [both laugh]. Umm..

FT: So, you have a certain amount of population and it is increasing and decreasing with different rates.
June: Yes!
FT: Okay. So, how does that show here?
June: umm.. [long pause]
FT: How do you apply that analogy to the case of force and motion?
June: So, you want it in terms of force? Is that right?
FT: mm hmm.
June: Not population then?
FT: umm, can you make a transition between..
June: Okay.
FT: . force and population?
June: umm.. [long pause]
FT: What are you thinking now?
June:  [laughs] I am just trying to remember the analogy more clearly so I can ..

(Interview Excerpt 5.2, April 12, 2000, lines 24-45)

June remembers a point in the discussion on March 3, 2000 which was counter intuitive for her. At that time, and still, the analogy helped her admit that when force becomes zero on an object, it does not have to stop if it has already been moving. We discuss how a varying population increase rate determines the number of people in a town. I give an example of a town where population is changing at times with different rates to explain how rate of change can be varying instead of steady (constant) at all times. After refreshing her memory I ask how June makes a conceptual connection between force and motion, how she explains the manifestation of a net force on motion.

FT:   It may increase and decrease at different rates. So, how does that apply to the case of force and motion?
June:  [pause] Well, that if it applies directly to the analogy you said, then the force can differ or can increase and decrease at varying rates like.. [pause]
FT:   Alright. How can I see the effect of force? [pause]
June:  You mean like pushing an object?
FT:   mm hmm. If you are applying a force on an object how can you see the effect of the force?
June:  By its motion.
FT:   Okay. By “motion” you mean?
June:  By the motion of the object how far it moves, how fast it moves.

(Interview Excerpt 5.3, April 12, 2000, lines 83-93)

June immediately thinks of her experiences with pushing an object. If pushed strongly an object is given a high initial speed and moves farther than otherwise. This example shows that she is not thinking of the effect of a net force on an object since, in real life situations, if an object is pushed and released, friction causes it to slow down and eventually stop. FT wants to learn if she also associates acceleration to force and motion. Although, June relates fastness (velocity or speed) directly to force and motion, she also seems to associate acceleration with fastness:
FT: And did we use a term for how fast it moves?

June: [pause] I can think of three times that [laughs] umm how fast it moves like velocity or speed or [pause]

FT: What's the third one?

June: Well, acceleration but that's the velocity of velocity, right?

FT: Okay, the velocity of velocity. What does that mean?

June: [pause] Well.. isn't velocity the rate of change of something speed? Then, it would be the rate of change of something speed and how fast that speed is changing.

(Interview Excerpt 5.4, April 12, 2000, lines 94-102)

The next task is to make a transition from the population example to force and motion. Population and its rate of change should correspond to velocity and acceleration, respectively, but June defines these relationships somewhat differently. Her descriptions are more like recollections of earlier discussions:

FT: So, how do you project the population analogy to this case? What in population analogy is velocity and what in population analogy is the acceleration?

June: umm [pause] velocity would be like whether the population is increasing or decreasing.

FT: Okay.

June: ..and acceleration would be whether it's increasing at an increasing rate or decreasing rate or decreasing at an increasing rate or decreasing rate.

FT: Okay. The rate of change of population.

June: Yeah, yeah!

(Interview Excerpt 5.5, April 12, 2000, lines 103-110)

4.3.3.2 The population analogy is good. But is it also useful?

I thought the responses to UVFQ on March 3, 2000 and the discussions held during that session served as an important learning opportunity for June. However, after four weeks, her responses to FMCE showed a retreat to her alternative conceptions as if she never had the previous tutoring interview. Today, after reviewing the population analogy, I want to inquire about another important issue: how and where she uses this information and whether she used it at all while responding to FMCE items.
FT: Alright, umm the next thing that I want to ask you is if you remember the last time I gave you a long questionnaire. While you were doing this did you at all remember the population analogy?

June: [fast and sharp] No! [laughs]

FT: No?

June: No.

FT: Umm, I mean never came to your mind?

June: Umm [pause] [sighs] the population analogy didn't come to my mind but the fact that of things increasing at an increa.. like the rate of change of increase or decrease came .. like I was thinking about that. Umm .. so .. I mean I possibly could have been thinking about population in the sense that the first time I've ever heard about something .. the concept of the rate of change of increase or the rate of change of decrease was in umm a biology class when we talked about umm is it ecology when you talk about like the population statistics?

FT: Demographics?

June: De.. okay, well we covered a section on that. So, I mean I might have sub- consciously thought of that but I didn't actually related back to this day when we talked.

(Interview Excerpt 5.6, April 12, 2000, lines 111-126)

This suggests that, first, rate of change is not a concept about which she is well informed. At the time it might have made sense to her to draw such a similarity between 'population increase rates' and 'rate of change of velocity' but that similarity apparently has not made a major contribution to her conceptions about force and motion.

4.3.3.3 "Does a constant force give you a constant acceleration? So, force has absolutely a direct correlation to acceleration."

Next I ask June to reconsider the first few FMCE items in the light of latest discussions. She describes what a steady increase of velocity means and how would that happen in the population analogy, but she does not immediately associate change in speed to acceleration.

FT: What comes to your mind when you read speeding up at a steady rate?

June: Well, tsk, that the sled is just gonna continuou.. continuously get faster and faster and it is gonna get faster at a constant rate.

FT: If you relate to any other concept that we talked about before?

June: The population would be increasing by the same amount each year.
FT: So, in the force and motion terminology it would correspond to what? [long pause]
How do you represent the increase or decrease of speed in force and motion concepts?
June: [pause] So, you mean that the force would be increasing at a steady rate each..
or the motion would be increasing at a steady rate because in this one what we
were saying that the force is like the population.
FT: Okay. Umm..
June: Or the velocity is like the population.
FT: I guess velocity is like population.

(Interview Excerpt 5.7, April 12, 2000, lines 133-145)

June initially associates an increase in population to an increase in force rather than
velocity. After she decides that population corresponds to velocity, I redirect her to think in
terms of acceleration.

FT: Umm. When you talked about you said acceleration is the velocity of velocity.
June: mm hmm.
FT: Right? So, when you talk about speeding up at a steady rate and what does that tell
you?
June: That the acceleration is gonna be constant or velocity of velocity,
FT: When it is changing at a steady rate so acceleration should be constant, right?
June: Yeah. [pause] So, does a constant force give you a constant acceleration?
FT: mm hmm.
June: It does?
FT: mm hmm. Do you remember $F = ma$.
June: Yeah. [See Figure 4.26]
FT: The mass is the same at all times. So, if you increase force you are increasing
acceleration. If force decreases acceleration decreases.
June: So, force has absolutely a direct correlation to acceleration.
FT: Correct.
June: Okay!
FT: And the ratio of force to acceleration is mass. Right?
June: Yeah. [softly]
FT: So, they are correlated. Like for example $F$ over $a$ equals $m$. If $m$ is constant, the
mass, to keep the left hand side constant, you know, if you increase $F$ you have to
increase $a$ by the same ratio or if you decrease $F$ you have to decrease $a$ by the
same rate.

(Interview Excerpt 5.8, April 12, 2000, lines 151-170)

June understands that increasing speed and constant acceleration follow from the
definition. It is not obvious, however, how constant force for this case became an option for
her, though it seems she is not really confident about it (see Figure 4.2 for June's journal
entry about a year ago). I try to explain the relationship in terms of a familiar formula. After
these discussions June answers the first three questions in FMCE fairly quickly and appropriately starting with the first question:

**June:** Okay. Then, I think I would want this to be B.

**FT:** B?

**June:** Yeah.

**FT:** Okay.

**June:** I don't know then because this question seems like it's asking the same thing. Oh, no, no, no! Because this is a steady velocity that would be like no increasing or decreasing just a constant rate.

**FT:** So, if the velocity is not increasing or decreasing its rate of change is what?

**June:** Zero.

**FT:** That means?

**June:** Acceleration is zero?

**FT:** That means? In terms of \( F = ma \)?

**June:** That..

**FT:** No force.

**June:** No force, yeah. Like the initial force would be it.

**FT:** You give it a certain speed and it goes with the same speed.

**June:** Yeah. Hmm.

**FT:** How about the third one?

**June:** [reads] "The sled is moving toward the right. Which force would slow it down at a steady rate?"

**FT:** So, it has a certain speed you wanna slow it down. Which means what is happening to the velocity.

**June:** Ahh. It is gonna be decreasing. Or..

**FT:** Each second it will be dropping by a certain amount.

**June:** Yeah. [pause]

**FT:** So, how can you do that? What kind of a force you need to apply?

**June:** Umm. A steady a constant force to the left.

**FT:** Yeah. Because \( F \) equals \( ma \)?

**June:** Yeah.

**FT:** Okay. You pointed that out.

**June:** [laughs] yeah!

**FT:** So, you see if you apply a constant force each and every time you'll be dropping the velocity by the same amount. Each instant the rate of change will be the same of the velocity. Makes sense now?

**June:** Yeah.

*Interview Excerpt 5.9, April 12, 2000, lines 171-206*

It is amazing to see that many things seemed completely new for June, although they were covered a number of times in the past. Particularly surprising is June's rare use of acceleration to describe motion in relation to force without a prompt or help. Although she looked like she gained some understandings during today's session, it is still questionable if
June will use the concepts of acceleration and force appropriately to describe motion in the future.
Chapter 5

RESULTS AND IMPLICATIONS

I don't know what's the matter with people: they don't learn by understanding; they learn by some other way – by rote, or something. Their knowledge is so fragile! ... This kind of fragility is, in fact, fairly common, even with more learned people. 
– R. P. Feynman (1985, pp. 36-37) 
from "Surely you are joking Mr. Feynman!" Adventures of a curious character

5.1 Introduction

The teacher-researcher in this study helped a novice student construct concepts of force and motion consistent with the Newtonian framework while at the same time carefully observing her learning. The purpose of this research study was to explore, describe, and explain the student's learning process in depth and in order to gain insights about the nature of her alternative framework and learning throughout a period of time. The research questions were:

4. What is the student's alternative framework about force and motion that she brought to the study?
5. How does the student respond to cognitive challenges about force and motion introduced by the teacher-researcher during group teaching and individual tutoring interview sessions?

6. How did the student's understanding of force and motion change during the course of this research study?

   a. What was the nature and extent of her learning after the group teaching and each individual tutoring interview session in spring semester 1999 and spring semester 2000?

   b. Why were the student's alternative conceptions persistent or subject to change?

The results of the study are discussed in terms of these research questions in the following sections. The chapter concludes with a discussion about contributions of this study to the literature and implications for further research and instruction.

Always trust the simplest explanation that fits all the facts unless there is a damn good reason not to do so.

–Dr. Stuart Hay
in *Incarnate*
by Ramsey Campbell
(Morrison, 1990, p. 99)

### 5.2 Question 1: June's alternative framework of force and motion

In this section June's alternative framework (as compared to the Newtonian framework) of force and motion are laid out separately for motion on a horizontal line and free fall. Additionally, the relationships she established between the concepts of force,
acceleration, and velocity are delineated from June's perspective. Table 5.1 presents the summary of results.

Table 5.1. Summary of the results regarding June's alternative framework of force and motion which was stable and persistent throughout the study.

<table>
<thead>
<tr>
<th>June's conception of force and motion can be characterized as pre-Newtonian (see section 5.2.1).</th>
</tr>
</thead>
<tbody>
<tr>
<td>- June articulated her conceptions in ways that are often labeled as 'Aristotelian physics' and 'Impetus physics'</td>
</tr>
<tr>
<td>- June held the conception that 'motion implies force'</td>
</tr>
<tr>
<td>- June related the strength of force on an object directly with magnitude of velocity ($F \propto s$)</td>
</tr>
</tbody>
</table>

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<tr>
<th>June's understanding of motion due to the earth's gravity is independent of Newton's laws (see section 5.2.2).</th>
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</thead>
<tbody>
<tr>
<td>- Initially June thought that heavier bodies fall faster than lighter bodies</td>
</tr>
<tr>
<td>- On the other hand, June had the conception that while moving downward on an inclined plane (e.g., biking downhill) the speed increased because forces behind the body increased</td>
</tr>
<tr>
<td>- Subsequently June revealed her conception that free fall is a natural tendency of displacement which occurs without a force acting</td>
</tr>
<tr>
<td>- June rejected the idea that the force of gravity depends on an object's mass, but due to gravity all objects are accelerated at the same rate during free fall.</td>
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</tbody>
</table>

<table>
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<tr>
<th>The relationships June established between force, acceleration and speed were:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- $F \propto s$ : Increasing force on an object means increasing speed and vice versa (see section 5.2.3)</td>
</tr>
<tr>
<td>- $F \propto a$ : Acceleration is merely an indicator of whether or not force on an object is increasing (see section 5.2.4)</td>
</tr>
<tr>
<td>- $a \propto s$ : Increasing acceleration on an object means increasing speed and vice versa (see section 5.2.5)</td>
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</tbody>
</table>

<table>
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<tr>
<th>June's understanding of Newton's laws:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- <strong>Newton's first law</strong>: All objects remain at rest unless a force is applied. If there is no net force (e.g., no constant push) on a moving object, it eventually comes to a stop (e.g., the initial force imparted to the object &quot;gets used up&quot; during motion) (see sections 5.2.3.1 and 5.2.4.1)</td>
</tr>
<tr>
<td>- <strong>Newton's second law</strong>: No notion of the second law in the Newtonian sense. June related force directly to speed and used acceleration merely as a figure of speech. Bypassing acceleration in this way suggests that she did not possess a appropriate conceptualization of the second law. This, in turn, created difficulties in understanding the first law and motion in the earth's gravity as well (see sections 5.2.3.2 and 5.2.4.2)</td>
</tr>
</tbody>
</table>
5.2.1 Junes alternative framework of force as a push or pull and motion on a horizontal line

The data regarding June's conceptions about force and motion on a horizontal line (motion in 1-dimension) are put together in an algorithmic representation in Figure 5.1. This alternative framework is inferred based on June's alternative conceptions that were fairly stable throughout the study. It shows how June 'sees' the working of the physical world and how she makes sense of information within the domain of force and motion; this is. Therefore, this knowledge structure displays June's experiences and observations in the physical world, how she reasons based on them (her inferences), and the interrelationships between them. Figure 5.2 shows an algorithmic representation of Newton's first and second laws of motion, an illustration of how an expert does or should structure her/his knowledge and reason about force and motion.

Newton's first and second laws define motion at non-relativistic speeds. Taken together, they represent a unified framework through the concept of acceleration. In this framework the first law is a special case and defines motion in inertial frames of reference where objects experience no force and hence no acceleration. On the other hand, the second law defines motion in non-inertial frames of reference where objects move under the influence of forces and experience an acceleration. Therefore, it does not matter if the motion is due to gravity or some other force (some sort of a push or pull); all can be explained via Newton's laws.
Figure 5.1. Algorithmic representation of June's alternative framework of force and motion in horizontal 1-dimensional, which was fairly stable throughout the study.
5.2.2 Junes alternative framework of gravity and free fall

During the study, motion in one dimension was also discussed with June in the context of free fall. June had various ideas about the gravitational pull of the earth and how it affected the motion of falling objects. She initially thought that heavier objects would "be forcing down more" so they would fall faster. Upon evaluating some cognitive challenges it looked like June abandoned this conception. She was aided in this by observing the free fall
of simultaneously dropped objects with different masses helped her adopting a new conception that objects, regardless of their masses, hit the ground at the same instant if dropped together from the same height. This new conception appeared to have considerable strength and persistence throughout the rest of the study. However, in explaining and coming to understand why they fell together she faced many conceptual difficulties.

Another conception June expressed several times was that gravity acts on all objects in the same manner regardless of masses. This conception was due to a numerical value she thought given to gravity; she "could remember something about 9 point 8 meters per second something." This gave rise to a construction for two objects of different masses falling together: "gravity is acting on both of them in the same manner." For her gravity became an influence on falling objects which produces equal speed even when it acts on different masses. Even when told it was actually the acceleration due to gravity which was uniform for all objects, June rejected this idea. Instead, she considered another alternative explanation: "It's like when things are falling you don't really need a force to get it somewhere, do you? I mean there is no like me pushing down on the object it just sort of drops and then its force or its weight carries it." Out of this confusion she decided to separate gravity from other forces making it a special force, one which has the same magnitude on all objects and always produces the same speed. As a consequence she rejected the applicability of Newton's second law to gravity "Now you said the masses are different but the acceleration is the same. Okay [suspiciously]. So, how can the force be different? So, you are saying this one takes more force to get it to fall? To get it to the ground it takes more force?" When asked whether the forces on two objects would be the same during free fall June responded "Through gravity? Yes! But like mass-wise, no."
June also demonstrated an understanding that gravity acts on objects continuously during free fall. For her, gravity was not a force that gets imparted to an object at the beginning of its motion. This is understandable since otherwise she would not be able to explain the speeding up during free fall.

To explain the motions of a toy car which is pushed up on a ramp, and, similarly, of a coin thrown up into the air June used the following three conceptions:

i) \( F \propto s \),
ii) Gravity is constant in magnitude and acts downward, and
iii) Gravity is applied on an object throughout its entire motion.

June's observations for such a motion were:

i) Objects slow down during motion against gravity,
ii) Objects speed up during free fall, and
iii) Objects come to a stop at the heights point of their flight.

When June combined her conceptions and observation to describe the motion she had a hard time explaining the zero velocity at the top since force as proportional to speed and gravity as always present conflict with each other (see section 4.3.2.3). Her resolution was that it would not be necessary to have a force at that instant. Her thinking also reflected the Aristotelian conception that a force is imparted to an object during the initial push; this force eventually gets used up during motion, causing the slow down. The action of gravity during the upward climb led June to think that the force on such an object gets reduced because of gravity and eventually vanishes at the top, leaving the gravitational force alone on the object. This way of imagining superposition of forces obviously does not obey the rules of vector algebra.

When two forces in opposite directions are added, the resultant force is in the direction of the bigger one and has the magnitude of the difference of magnitudes of original
forces. Thus, it is thought that only this resultant force acts on the object. June's way of imagining the same situation was that one force gradually and continuously causes the other to diminish and then when they are in the same direction one is having the other develop more and more in time as the object acquires speed.

It can be concluded that June's thinking of gravity and free fall does not include the concept of acceleration. Just as in the case of horizontal motion in one dimension she tries to put all the ideas together rationally. However, since such an alternative framework lacks the necessary coherence and simplicity, it created unintended and unsuccessful learning outcomes for June's case.

5.2.3 The relationship between force and velocity

June 'sees' a direct relationship between applied force on an object and the speed it will gain as a result ($F = \dot{s}$). June often assumes the existence of friction even if it is indicated that "friction is ignored" or the force on the object is the "net" force. When a problem is presented to her June tends to think in terms of her experiences and observations and compares the problem situation to situations she knows. When it is said that an object is pushed with a constant net force or with a constant force of certain strength (magnitude) on a frictionless surface, she understands these statements to mean that someone is pushing an object at a constant pace by moving at a steady speed (see figure 5.4). Therefore, she concludes that the object will move with a constant speed as a result of applying such a force.

On the other hand, a net force or an applied force in the absence of friction means that there are no other forces considered and the motion will be predicted due to this force
only. The ideal situation of frictionlessness cannot be matched to any real life situation because in daily life friction always exists. The only exception is in considering the outer space. Not surprisingly, when a force-motion problem is presented in the context of outer space, June is able to respond intuitively and scientifically. Hence, June's understanding of the idealized situations in problem statements is an important part of the issue for delineating her alternative framework and the nature of her learning.

Figures 5.3-6 show four situations where an object is moved by applying a force as shown. In situations such in Figures 5.3-5 what a person actually does is to keep the object moving at a certain speed by applying a force as needed. Since friction always exists and can be quite large, it is often difficult to accelerate large objects by means of a constant force. In such situations, indeed, the speeds of objects change constantly; speed increases (the object accelerates) at times when a force is applied and friction causes a subsequent slow down. But another application of a force by pushing, pulling, or rowing increases the speed again. Therefore, even when it appears that the person is applying a constant force which produces a constant speed, the applied force often just complements the friction force once the object is set in motion.

When one pulls/pushes harder or rows more aggressively, then, speed increases during that period accordingly. In order to keep objects moving at a certain speed, one should continue to applying the force as frequently as needed to maintain that speed. Consider pushing a shopping cart while moving around. It is the pace of the person that determines how much push is going to be exerted on the cart. Therefore, in this context 'pushing at a constant rate' might mean keeping a constant pace. Such an experience or
observation gives rise to a conception that the stronger the successive pushes one exerts the faster the object moves on the average.

The flaw in this conception is that it does not consider the existence and influence of friction, so the applied constant force is not the net force mentioned in Newton’s laws. Figure 5.6 shows a situation where Newton’s second law can more readily be observed. Once the system is released, assuming the cylindrical object is heavy enough to exert more force to the left than the resistance of friction towards the right, the speed of both objects continuously increases at the same rate since they move under the influence of a net force which causes the system to accelerate. This acceleration can be calculated by applying Newton’s second law:

\[ F_N = m_s a_s \]

\[ \Rightarrow F_1 - F_f = (m_c + m_b) a_s \]

\[ \therefore a_s = \frac{(F_1 - F_f)}{(m_c + m_b)} \]

where \( F_N \) is the total net force, \( m_s \) is the total mass, and \( a_s \) is the acceleration of the system; \( F_1 \) is the force towards the left which is equal to the weight of the cylindrical object, \( F_f \) is the friction force towards the right on the box load; \( m_c \) is the mass of the cylindrical object, and \( m_b \) is the mass of the box load.

If \( F_N \) yields zero, meaning that \( F_1 \) is just overcoming the resistance of \( F_f \), then the system will have no acceleration \( (a = 0) \). According to Newton’s first law of motion (see Figure 5.2), if the system is not disturbed it will stay at rest; if it is given an initial speed it will move with that speed remaining unchanged.
Figure 5.3. Pulling a load by using a rope.

Figure 5.4. Pushing a load by direct contact.

Figure 5.5. Rowing as an example of motion at a constant speed.
Figure 5.6. An illustration of constant force causing a constant acceleration and hence speeding up.

Another example of conceiving force as being proportional to speed surfaced while discussing free fall (see section 4.2.4.11, Interview Excerpt 1.1.14, and Figures 4.16). Explaining free fall by means of forces applied on objects due to the earth's pull was very confusing for June. She thought that since heavier objects "weigh more and are pulled down harder" with greater forces they ought to fall faster. Her view of free fall disregarded inertial property of masses since she did not consider force as a product of mass and acceleration. Instead, June established a direct proportionality between the force applied on an object and its speed \( F \propto s \).

5.2.3.1 Newton's first law of motion

Newton's first law of motion defines the state of an object while under the influence of no net force. That is, it might either be a situation where no forces exist on an object (in
some hypothetical corner of the space), or the forces on an object cancel each other out and give no net force. In physics problems both of these situations are considered. When horizontal motion is considered no applied force on a frictionless environment is an example of the former (except the normal forces), while equilibrium in the presence of several forces exemplifies the latter. Equilibrium conditions were discussed in the first unit of the course June took during spring semester 1999 just before the unit in which she was selected to participate in this study. Although, it is relatively easy for many students to understand intuitively the condition of equilibrium of several forces, ignoring friction seems to be much less conceivable.

June thinks of four situations of how speed of an object becomes zero (see Figure 5.1). First, the forces may be in equilibrium on an object at rest. This suggests that she correctly identifies force as the cause of motion from rest. Second, when an object is pushed and released a velocity is imparted to it which "gets used up" during motion (impetus theory of motion). Then, the final state of the object is a full stop when the speed gradually lessens and finally vanishes. Third, the force on an object becomes weaker and weaker eventually becoming zero; the speed then becomes zero as well. That is, one needs to push an object continuously with the same strength to keep it in motion with constant speed. Therefore, no force implies no motion. Fourth, the application of a force in the direction opposite to motion can instantaneously stop the object. Although the first and second cases (in the absence of friction) are related to Newton's first law, the third and fourth cases are concerned with Newton's second law since any net force causes a change in speed according to its strength and the mass of the object. Therefore, it can be concluded that June has confusion as to where to apply which law consistently. She does not discriminate between
equilibrium conditions and presence of net force to define a state. She does not consider initial conditions to determine an object's subsequent motion.

5.2.3.2 Newton's second law of motion

June's conceptions of force and motion revealed characteristics of both Aristotelian and Impetus physics. She strongly held the conception that in order to maintain a certain speed, a force of certain strength needs to be applied on it continuously. She also explained situations involving a push and release of an object with the descriptor "force getting used up" as the object slows down.

To explain the slow down during upward motion against gravity June used a special way of adding forces (vectors). Since the downward gravitational pull continuously acts on such an object and the force is proportional to its speed, the initially imparted force gets weakened by the force of gravity, eventually overcoming it and pulling the object back down. As the object gains speed the force on it gets increased as well. Though, during horizontal motion the absence of force causes an object to stop, during an upward throw an object stops without the force disappearing.

Newton's second law, on the other hand, explains such situations with a single principle: acceleration is linearly proportional to the force applied on an object. Therefore, an object only slows down due to the presence of an opposing force. Since the first law states that moving objects do not "carry" force the only force present during an upward climb is the pull of the earth; this causes the steady slow down. Since the same force is present at all times, after the object stops at the top it begins accelerating toward the ground.
at the same rate it was slowing down. But such a motion under the influence of a constant force is not conceivable to June. Since acceleration is not the central concept to explain motion, Newton's second law never became comprehensible, although she was able to give definitions accurately of both force and acceleration.

5.2.4 The relationship between force and acceleration

Several times throughout the study June demonstrated that although she memorized and retained the definition of acceleration she did not use it in the sense a physics expert would. Though acceleration plays a very central role in understanding motion within the Newtonian framework, June has no place in her alternative framework for acceleration (see Figures 4.13 and 5.1).

June understands acceleration as proportional to force since, for her, increased force means increased speed (see section 4.2.5 and Interview Excerpts 1.1, 1.9, 1.14, 1.23, 2.2, and Figures 4.13 and 4.16). Since, for her, the definition of acceleration is "speeding up," increased speed thus implies increased acceleration and vice versa.

5.2.4.1 Newton's first law of motion

Typically, June associates constant speed with constant force and acceleration. However, according to the definition of acceleration if speed does not change acceleration becomes zero, since acceleration gives how fast speed changes over time. Newton's first law implies that at rest condition is also a case of zero acceleration (see figure 5.2). Since, for June, force and speed are directly proportional, even though she accurately recites the
definition of acceleration she uses it just as a figure of speech. It can be concluded from the data that June does not have an understanding of Newton's first law as it relates to acceleration.

5.2.4.2 Newton's second law of motion

Since June has no place for acceleration in her alternative framework for acceleration, this creates a deficiency in her understanding of motion in relation to force. The most inconceivable idea for her was having a constant net force on an object to cause speeding up. This difficulty was revealed several times throughout the study. According to her, greater force caused greater speed; therefore, reducing the force caused lower speed. Although pushing an object with an increasing net force causes it to speed up, according to Newton's second law a lessening net force can increase speed as well. The difference between these two cases is that the rate of increase of speed gets higher in the former while it gets lesser in the latter. The idea is that any net force causes speeding up whether it gets stronger, weaker or stays constant when applied on an object throughout a period of time.

5.2.5 The relationship between acceleration and velocity

Since June was committed to the conception that greater speed meant greater acceleration, she was not able to grasp the definition of acceleration. Newton's second law formulated as \( F = ma \), that is, force is linearly related to acceleration. Establishing the relationship between force and speed requires understanding the definition of acceleration, 'time rate of change of velocity.' June's naive relation of acceleration to speed kept her from
understanding the possibility of slowing down with an increasing acceleration. From the definition of acceleration it follows that if an object is experiencing a change in speed, whether increase or decrease, it has an acceleration. In this way, the rate of the change in speed determines the magnitude of acceleration. Therefore, an object might be subject to a huge acceleration if its speed diminishes abruptly. For instance, traffic accidents often involve vehicles, individuals, or objects undergoing sudden changes in velocity. The bigger the change in velocity, the bigger the acceleration, and hence the bigger the force exerted on objects become. But, for June acceleration is merely an indicator of whether an object is speeding up (see section 4.2.5; Interview Excerpts 2.3, 2.4, 2.5, 2.7, 2.10, 2.17; Figures 4.13 and 4.16).

5.2.5.1 Understanding rate of change

Understanding acceleration in conjunction with the concept of rate of change presented a real challenge for June. The only place that she had studied 'rate of change' before was in relation to population growth in a high school biology class (see Interview Excerpt 5.6). As a result of discussions about acceleration June made a connection to her prior knowledge by realizing the similarity between the role of rate of change in population problems and the role of acceleration on velocity (see section 4.2.6.2). However, although during the tutoring interview sessions she seemed to be developing an understanding of the concept and its relationship to acceleration (see sections 4.2.6 and 4.3.1), it was not sustained in the long term as a learning outcome as the follow up interview data show (see section 4.3.3).
... in a broad sense, everything is a case. The word case just refers to an experience. (p. 11) People reason from experience. They use their own experiences if they have a relevant one, or they make use of the experience of others to the extent that they can obtain information about such experiences. An individual's knowledge is the collection of experiences that he has had or that he has heard about. (p. 7)
– Riesbeck & Schank (1989)

5.3 Question 2: June's responses to cognitive challenges about force and motion

A summary of the results of this study regarding June's responses to cognitive challenges about force and motion are presented in Table 5.2. These results are elaborated in the remainder of this section.

Table 5.2. June's responses to cognitive challenges about force and motion.

- Majority of cognitive challenges did not create a strong dissonance for June
- Although cognitive resolutions were reached during discussions, in the long-term, they did not lead to a substantial conceptual change in June's conceptions
  - Although June seemed to be undergoing conceptual development during tutoring sessions, in the long term she merely learned and retained the definition of acceleration
- June's alternative framework of force and motion stayed intact throughout the study

Throughout the research study FT interacted with June as a teacher-tutor. During this time many opportunities were taken to facilitate June's learning of force and motion through conceptual resolution between her alternative conceptions and the Newtonian concepts. As a result a conceptual change and development were expected in her learning. To achieve these goals several cognitive challenges were introduced during discussions; these cognitive challenges also served as means of in-depth explication of her alternative
conceptions and framework which in turn provided FT feedback for planning the following sessions.

FT used a variety of cognitive challenges in the form of experiments, demonstrations, thought examples, and scientific explanations of terms throughout the study. These were:

- Newton's second law and acceleration as rate of change of velocity,
- Inclined plane and a constant force causes acceleration,
- Free fall: Experimenting with two objects of significantly different mass,
- The outer space idea,
- Combining horizontal motion with free fall,
- June's population analogy, and
- UVFQ (the instrument prepared by the researcher).

The data reveals that except experimenting with different masses to determine if heavier objects would fall faster, no other conceptual challenge created a strong dissonance for her. Although temporary cognitive resolutions were reached during discussions, they did not lead to any long-term conceptual change.

Despite having seemingly successful tutoring sessions regarding the role of acceleration in explaining force and motion and although June learned and retained its definition, her knowledge of acceleration did not become procedural. The inclined plane demonstration and discussions around it were very surprising for all four students in the small group since it created a cognitive conflict between their expectancies and observations. As a result of discussions, June came to a resolution as "I now realize that the force is not gonna change unless the slope doesn't change." A rule was formulated in class after the discussions: "a net constant force makes an object speed up." However, such realizations during the course of the study did not create a substantial conceptual change.
As indicated earlier, observing free fall of two different masses dropped from the same height at the same instant and seeing that they hit the ground at the moment helped her to overcome her old conception that heavier objects fall faster. Therefore, it can be concluded that this experiment created a strong conflict in her conception and led to a conceptual change. Yet, June's explanation of why 'mass' is not a factor in determining an object's speed during free fall was not scientific. For purposes of achieving meaningful learning, this kind of knowledge is more important than merely memorizing facts.

The 'outer space' idea as an example of frictionless motion made sense to June; with it, she was able to predict motion according to Newton's laws. This suggested that when June had to think about and explain motion her ideas were highly contextual. Rather than using a coherent set of principles (i.e., Newton's laws) to explain different situations, she was building a library of facts which were fragmented in nature. She tried to be rational and develop rules on which to base her thinking, but the fragmented contextualization of her knowledge demonstrated itself in explanations of the same phenomena in different ways when presented in different contexts. Therefore, integration and invariance (diSessa, 1998) of conceptual knowledge were not realized in the case of June's learning.

5.4 Question 3: Change in June's understanding of force and motion

June's learning can best be described as building a library of expectations, facts, and definitions rather than a meaningful expert-like knowledge structure of involved concepts. Her learning, in general terms, gives correspondences to cases with which she became acquainted during instruction rather than using related concepts to reason about them.
When June attempted to work through dissonances, she often ended up with unintended learning outcomes (e.g., see interview excerpts 1.12 and 4.4). When her alternative conceptions are examined throughout the study the data reveals that her alternative framework (see section 5.2 and Figure 5.1) was not altered by her experiences during the study.

Table 5.3 presents a summary of results regarding change in June's understanding of force and motion. In the following sub-sections June's learning will be evaluated by examining the small group instruction and each tutoring interview session. Additionally a conclusion will be drawn about the nature of her learning.

Table 5.3. Change in June's understanding of force and motion

- Even though June was successful in acquiring declarative knowledge, she was not making transition to knowing why and how in terms of Newton's laws (see section 5.4.1)

- In June's framework acceleration virtually did not exist in the Newtonian sense. June's framework of force and motion can be characterized as a stable state which was disturbed slightly during each teaching/tutoring session but was not transformed substantially. Created conceptual dissonances during small group instruction and tutoring interviews led June towards temporary cognitive resolutions, but these were not sustained in the long term (see section 5.4.2)

5.4.1 The nature and extent of June's learning after the group teaching, and each individual tutoring interview session

5.4.1.1 In spring semester 1999

During spring semester 1999, FT interacted with June as a teacher of the small group instruction and as a tutor during the two interviews. Additional data were collected from the
pre-test, June's journal entry after the three classroom sessions, the post-test, and the word association task.

June's reaction to classroom discussions and her journal entry in which she summarized her learning indicate that she faced cognitive challenges and learned some useful information about force and motion. However, the first interview indicates that she was still having the same conceptual difficulties. This tutoring interview was another time when Newton's laws were discussed both in the context of horizontal motion and free fall. FT was under the impression that this was a positive learning experience for June.

The post-test data, 2 weeks after the first tutoring interview, revealed that although she was able to give definitions correctly, she was not successful in applying them to different situations. Her answers reflected almost no conceptual gain. This finding was further supported by the second interview which gave further insights to the source of June's conceptual difficulty. Although acceleration has a very central role in describing motion in the Newtonian framework, for June it barely exists. She thought of acceleration as merely 'speeding up.' Such a notion of acceleration is consistent with the daily use of the term. It also refers to a change in speed. However, since June's conception of the relationship between force and speed was Aristotelian in nature, she used acceleration chiefly as a simple figure of speech. Whatever definition of acceleration was given June took without making any corresponding change in her alternative framework of force and motion. She may have thought it was the "scientific definition" that she did not know before and she was expected to learn (memorize). But she never seemed to doubt her alternative framework of force and motion. Therefore, the scientific definition of acceleration and her alternative framework co-existed without ever interacting with each other.
The second tutoring interview session was planned to make the implicit relationships between force, acceleration, and velocity explicit for June by discussing the formula $F=ma$. Imagining a situation where a constant force produces a constant acceleration which results in increased speed was inconceivable for her (see interview excerpt 2.3). However, the discussions on Newton's laws, in relation to the formula $F=ma$, proved useful, and toward the end of the interview there came a breakthrough. June thought that the concept of acceleration was very similar to rate of change of population (see interview excerpt 2.3) where a decrease did not necessarily mean a decrease in population. This was a major step in understanding the meaning of acceleration and its relationship to force and velocity, and appeared to be a sign of conceptual development.

5.4.1.2 In spring semester 2000

One year later June's learning was probed again, this time with a true/false questionnaire (UVFQ) that was based on her alternative conceptions and framework as revealed during spring 1999. June's initial responses showed a complete retreat to her alternative framework without any signs of conceptual development from the year before. The discussions, which lasted about 90 minutes, opened up another opportunity for June's learning.

Four weeks later, June took the FMCE to demonstrate her learning of force and motion so far (see Appendix B). It was very interesting to see that although June could articulate a proper understanding of motion on a frictionless surface, she was not able to respond to similar items presented in the test appropriately. On the other hand, June
responded differently than before for the case of slowing down. This is perhaps due to the
discussions during the previous interview in which she realized that an opposing force does
not stop an object immediately. Even more interesting is the difference between how she
responded to the cases of speeding up and slowing down. This comparison shows that even
if she demonstrates a correct understanding it cannot be easily attributed to a conceptual
development. This result becomes more sustained when one considers her questioning of
the direct relationship between force and acceleration two weeks later. Similarly, although
June was able to describe the motion of an upward thrown object, knowing gravity is always
present on all objects, her explanation of forces and acceleration were far from being
Newtonian.

5.4.1.3 Summary

Each subsequent probe during tutoring interview sessions revealed that June was not
undergoing a conceptual change; instead, she was strongly holding to her alternative
conceptions. This, in turn, suggested that her alternative framework was remaining largely
intact contrary to FT's impression that his tutoring was helping June develop conceptually.
Her learning was restricted to maintaining what was happening during each event, but such
observations were not translated into meaningful learning. In short, even though June was
able to get to know that, she was not making transition to knowing why and how in terms of
Newton's laws. June's alternative conceptions were significantly different than the intended
learning outcomes (the Newtonian framework), and, despite her learning during the course
of this study, she did not get to 'see' the physical world through the physicist's goggles.
5.4.2 Why were June's alternative conceptions persistent or subject to change?

The data gathered through this research study suggest that June's knowledge base consisted mostly of declarative knowledge. She knew the definitions of concepts and the descriptions of the way events unfold in the correct sequence. But the procedural knowledge she possessed about force and motion was significantly different from an expert's. Throughout her interaction with FT the focus was on both facts and procedures about how force and motion relates to each other according to the Newtonian framework. Even though June was able to learn much factual information, even if it contradicted her prior knowledge, there was a blockage on her learning of the procedures that were new to her. This could be best illustrated by June's learning the definition of acceleration but not being able to apply it in given situations.

From the physicists' point of view it is assumed that all objects behave the same way under the same conditions, and physicists explain the motion of objects according to the net force being exerted on them. The concept of acceleration defines the transition from applied net force to observed speed of objects, and a seemingly diverse set of observations is integrated into a single conceptual framework. June's framework, on the other hand, was significantly different from an expert's (see Figures 5.1 and 5.2). The data reveals that in her alternative framework, acceleration virtually did not exist in the Newtonian sense. Since acceleration plays a unifying role in explaining motion in relation to force, June's lack of understanding of acceleration significantly hindered her learning.

It was also observed that, during teaching and tutoring, conceptual dissonances led June to temporary cognitive resolutions which were not sustained in the long term. Her understanding of force and motion can be characterized as a stable state which was
disturbed slightly during each teaching/tutoring session but was not transformed. It can be concluded that the body rejected the transplanted new organ.

### 5.5 Concluding remarks

This case study delineated one student's alternative framework and nature of learning during interaction with the teacher-researcher over a long period of time. Through this study one student's alternative conceptions and the relationships that she established between them were explored, described, and explained. Descriptive information about the nature of the student's conceptual development and obstacles in her learning were gathered. The study illustrated the complexity of learning force and motion concepts in relation to one's alternative conceptions and framework. Additionally, insights into teacher-student interaction, and student-subject matter interaction were revealed.

The study demonstrated the role of a researcher as the most essential instrument in a qualitative case study. It exemplified researchers' need to possess both a deep subject matter knowledge and effective research skills. Also, the importance of triangulating the sources and methods of data collection for the purposes of minimizing the negative effects of researcher bias and shortcomings of the interpretation processes was revealed. Performing interpretations and analyses of data on an on-going basis throughout the research study proved to be an advantageous strategy because it allowed the researcher to highlight significant emerging themes in the data.
5.5.1 Summary of results

1. June's alternative framework, as constructed from her conceptions, reflect a totally different point of view than the Newtonian framework regarding force and motion. Additionally, even though from an expert point of view all motion can be explained by the same set of rules (Newton's laws of motion), June considers free fall different than motion in horizontal one dimension and gravity different than a push or pull on horizontal surfaces.

2. Although June often stated that acceleration changes in the same manner as the net force on an object, this did not reflect a 'true' understanding of Newton's second law of motion. Acceleration merely meant to her *speeding up* which was understood as being 'pushed/pulled harder and harder.' Therefore, loosing speed was due to being 'pushed/pulled less and less' which was correspondingly equated to less acceleration. In her framework, moving at a constant speed required a net constant force being applied. Since in such a situation speed was not increasing, June thought acceleration remained constant as well in accordance with its definition.

3. During interaction with the teacher-researcher (i.e., short small group instruction and tutoring interviews) June appeared to develop conceptually. However, each subsequent session with her revealed that she reverted back to her original alternative framework. That is, most of June's preconceptions were unaffected by the cognitive challenges emerged during the sessions and as a result her alternative framework remained intact.

4. Although June memorized and retained many of the definitions throughout the study they remained as external attachments to the existing alternative framework rather
than having an impact of change on it. It can be concluded that despite the teacher–researcher's all efforts the central role of acceleration, in understanding force and motion according to the Newtonian framework, was not conveyed to June.

5. The research study revealed that, in the case of June, together with learning about concepts individually it is essential to develop an understanding of the required relationships between the concepts in a domain in order to attain a meaningful learning as a result of instructional activities.

5.5.2 Limitations

This study also possessed several limitations due to its design and nature. First, there was only one researcher who designed the study, performed all steps of data collection, and prepared, interpreted, and analyzed the data. A need for researcher triangulation for such studies was felt throughout the study. Another limitation came from the study's focus on a single student even though she was chosen from among a group of peers. Despite the insights provided into students' alternative conceptions, framework, and learning process, the results are not generalizable to a population such as non-major female freshmen. Lastly, since the participant's learning outcomes did not reflect a fully developed conceptual framework of force and motion, the results of the study are limited to the early phases of her learning. Thus, this study suggested the nature of conceptual obstacles in learning and, indirectly, how they might relate to achieving meaningful learning, but it did not provide data for realizing meaningful learning per se.
5.6 Implications

This research study has several implications for future research and for teaching. Below are the researcher's suggestions.

5.6.1 Implications for Research

It is deemed important and worthwhile to study students' learning over an extended period of time (Niedderer, 1997; Petri & Niedderer, 1998; Taber, 2000; diSessa & Sherin, 1998, diSessa, in press). Studies that explore, describe, and explain the nature of learning on-site and in-progress from beginning to end throughout one's learning process that end up in successful conceptual development may provide insights into the nature of students' interaction with subject matter and nature of conceptual change and development.

During this study June's alternative conceptions regarding force and motion were explored and identified. The UVFQ (see section 4.3.1 and Figure 4.16), developed by the researcher based on June's conceptions, may provide a viable model of students' alternative conceptions. Therefore, perhaps with the addition of new questions about how acceleration relates to force and speed, opportunities for administering this instrument should be pursued in different other institutions on various age groups.

June's alternative conceptions demonstrate that she does not have a notion of acceleration in the Newtonian sense and she relates speed directly to force. Thus, this study suggests that understanding acceleration apparently plays an essential role in one's construction of a framework of force and motion (see Figure 4.13 and Figure 5.1). The centrality of acceleration needs to be explored among a large group of students through a
research design that will allow differences in learning to be explained among students who can fully incorporate acceleration into their framework and those who cannot.

This study raises important questions about what constitutes learning a concept, including:

- What is a concept? Can a concept be defined or learned in complete isolation from other related concepts?
- Are there concepts like acceleration in other domains of physics and in other fields of science which are so central in defining a whole framework?

Pursuing answers for the above questions may yield important consequences for teaching and learning school science topics.

June, the participant student in this study, suggested an analogy (population growth) which might be fruitful in teaching the concept of acceleration. Viability of this and other related analogies (e.g., inflation rate in an economy) should be studied to find out how best they can be utilized in teaching force and motion.

June's learning illustrates one in which students, as happens in many cases, collect factual information and build a 'library of related situations' rather than conceptually integrating presented information. This might originate from not knowing what the big picture is or where the instruction is headed. Further in-depth investigations of student learning might help describing and explaining exemplary cases of successful learning.

### 5.5.3.2 Implications for Instruction

This research study demonstrated a case of one student's learning of force and motion. The student had persistent alternative conceptions which guided her learning throughout the study. Data revealed that while responding to questions presented to her she
was thinking of real life situations so that she could relate the questions to her experiences. This suggested that it might be useful to explicitly describe how the scientific theories, laws, and models relate to real life situations and students' experiences. Although usually during classroom discourse teachers discuss what laws imply, what they do not imply is left to the students to infer. Showing both sides of a coin might give a better picture of it leaving less room for a possible misinterpretation. Ideal situations, like frictionless surfaces, are often used in physics problems to avoid unnecessary complications. Before discussing such cases, which do not exist in real life situations, how the phenomenon exhibits itself naturally and how it is explained scientifically should be discussed, so that students can better make sense of the ideal situations.

Newton's first and second laws of motion are complementary and relate to each other via the concept of acceleration. The results of this study illustrate that without achieving a substantial meaningful learning of the concept of acceleration a student will continue to hold onto her/his alternative framework of force and motion. Therefore, classroom teaching of force and motion should emphasize and revolve around the concept of acceleration and its relationship to force and speed.

The results also suggest that being able to state consistently the correct definition for a concept does not always mean that meaningful learning is taking place. Rather than teaching the concepts of force, velocity, and acceleration in isolation and separate from one another, the Newtonian framework (see Figure 5.2) needs to be taught explicitly to students by showing how different it is from a naïve framework such as in Figure 5.1.
Most textbooks (e.g., Serway, 1992) first cover kinematics preceding Newton's laws. Kinematics is the foundation where velocity and acceleration are defined while Newton's laws relate force to motion.

Acceleration can be defined through its relationships to change in velocity and to force (Newton's second law). Both definitions were introduced to June during the study. It was hoped that she would be able to reconcile these two definitions. However, June had an alternative conception of acceleration. For her acceleration was merely 'speeding up.' She also strongly associated increasing speed with increasing force. Although June could memorize the definition of acceleration as "the rate of change of velocity" she might have maintained it as the 'fancy scientific way' of saying 'getting faster.' Therefore, physics teachers need to be aware that just providing definitions of such concepts is not likely to help the students to grasp what is truly meant by them. Students might have alternative descriptions which often might include same or similar words. Hence reading the scientific definitions might give the student an illusion that what s/he already knows is indeed correct and nothing needs to be changed. Explicitly addressing the differences between scientific definitions and novice definitions might help learners to distinguish between them.

Similarly, Sandberg and Barnard (1997) also encountered unsuccessful student learning in a domain of science. They evaluated the learning environment, the students, and the domain for possible causes of the attained results since they are often at the center of immediate focus of attention. However, their results implied that lack of the construction of complex declarative knowledge and self-assessment were the main problem area rather than the above cited three external factors. Hence, they suggested that students should also
acquire meta-cognitive skills and learning strategies through an active cognitive construction process.

When June's cognitive processes are examined it can be concluded that although she was engaging in the learning activities, in the long term she was not engaged in a self assessment of her own learning. Once she had an understanding of the meaning of a concept congruent with the intended learning outcomes she could have been encouraged to compare and contrast it to her corresponding alternative conception and perhaps maintain a log of such developing insights in a learning portfolio. Results also suggest that June was lacking the knowledge of the *domain structure* and the relationship between the *processes*. Successful teaching should help students build a knowledge structure consistent with that of the expert community.
REFERENCES


APPENDIX A
INFORMED CONSENT PROCEDURE

Throughout this study I complied with the rules and regulations of the Office of
Regulatory Compliance (ORC) for use of human subjects. The research proposal was
examined before beginning of data collection and an expedited review approval was granted
by the ORC (ORC#990133-00) on February 2, 1999. Modifications in the study and
extension requests were also reviewed by the ORC and to approval to continue research was

All participants were informed about the nature and purpose of the study and the
specific tests that were administered. Participation was voluntary and students had the
freedom to withdraw from the study without any penalty.

Informed consent forms were utilized and signed by all participants in every phase of
the study. The forms are on file in the Penn State University, Office of Regulatory
Compliance, 212 Kern Graduate Building.
APPENDIX B

FORCE AND MOTION CONCEPTUAL EVALUATION TEST AND JUNE'S RESPONSES

TOOLS FOR SCIENTIFIC THINKING: FORCE & MOTION CONCEPTUAL EVALUATION

Directions: Answer questions 1-43 in spaces on the answer sheet.

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

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

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

A. Which force would keep the sled moving toward the right and speeding up at a steady rate?
B. Which force would keep the sled moving toward the right at a steady (constant) velocity?
F. Which force is moving toward the right. Which force would slow it down at a steady rate?
G. Which force would keep the sled moving toward the left and speeding up at a steady rate?
D. The sled was started from rest and pushed until it reached a steady (constant) velocity toward the right. Which force would keep the sled moving at this velocity?
F. The sled is slowing down at a steady rate and has an acceleration to the right. Which force would account for this motion?
B. The sled is moving toward the left. Which force would slow it down at a steady rate?
8-10 refer to a toy car which is given a quick push so that it rolls up an inclined ramp. After it is released, it rolls up, reaches its highest point and rolls back down again. *Friction is so small it can be ignored.*

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

- **A** Net constant force down ramp
- **B** Net increasing force down ramp
- **C** Net decreasing force down ramp
- **D** Net force zero
- **E** Net constant force up ramp
- **F** Net increasing force up ramp
- **G** Net decreasing force up ramp

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

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

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

11. The coin is moving upward after it is released.
12. The coin is at its highest point.
13. The coin is moving downward.
Questions 14-21 refer to a toy car which can move to the right or left along a horizontal line (the positive part of the distance axis).

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

A force is applied to the car. Choose the one force graph (A through H) for each statement below which could allow the described motion of the car to continue. You may use a choice more than once or not at all. If you think that none is correct, answer choice J.

A. 14. The car moves toward the right (away from the origin) with a steady (constant) velocity.

B. 15. The car is at rest.

C. 16. The car moves toward the right and is speeding up at a steady rate.

D. 17. The car moves toward the left (toward the origin) with a steady (constant) velocity.

H. 18. The car moves toward the right and is slowing down at a steady rate.

E. 19. The car moves toward the left and is speeding up at a steady rate.

J. 20. The car moves toward the right, speeds up and then slows down.

C. 21. The car was pushed toward the right and then released. Which graph describes the force after the car is released.

J. None of these graphs is correct.
Questions 22-26 refer to a toy car which can move to the right or left along a horizontal line (the + distance axis). The positive direction is to the right.

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

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

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

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

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

G 27. The coin is moving upward after it is released.
D 28. The coin is at its highest point.
B 29. The coin is moving downward.
Questions 30-34 refer to collisions between a car and trucks. For each description of a collision (30-34) below, choose the one answer from the possibilities A through J that best describes the size (magnitude) of the forces between the car and the truck.

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

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

A. 30. They are both moving at the same speed when they collide. Which choice describes the forces?
F. 31. The car is moving much faster than the heavier truck when they collide. Which choice describes the forces?
B. 32. The heavier truck is standing still when the car hits it. Which choice describes the forces?

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

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

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

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

A. The force of the car pushing against the truck is equal to that of the truck pushing back against the car.
B. The force of the car pushing against the truck is less than that of the truck pushing back against the car.
C. The force of the car pushing against the truck is greater than that of the truck pushing back against the car.
D. The car's engine is running so it applies a force as it pushes against the truck, but the truck's engine isn't running so it can't push back with a force against the car.
E. Neither the car nor the truck exert any force on each other. The truck is pushed forward simply because it is in the way of the car.
J. None of these descriptions is correct.

A. 35. The car is pushing on the truck, but not hard enough to make the truck move.
C. 36. The car, still pushing the truck, is speeding up to get to cruising speed.
C. 37. The car, still pushing the truck, is at cruising speed and continues to travel at the same speed.
B. 38. The car, still pushing the truck, is at cruising speed when the truck puts on its brakes and causes the car to slow down.
D. 39. Two students sit in identical office chairs facing each other. Bob has a mass of 95 kg, while Jim has a mass of 77 kg. Bob places his bare feet on Jim’s knees, as shown to the right. Bob then suddenly pushes outward with his feet, causing both chairs to move. In this situation, while Bob’s feet are in contact with Jim’s knees.

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

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

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

A. 40. Which velocity graph shows the car moving toward the right (away from the origin) at a steady (constant) velocity?

B. 41. Which velocity graph shows the car reversing direction?

C. 42. Which velocity graph shows the car moving toward the left (toward the origin) at a steady (constant) velocity?

D. 43. Which velocity graph shows the car increasing its speed at a steady (constant) rate?
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Scholarly Work

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