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Between the Poles: Locating Physics Majors in the Expert-Novice Continuum

A Dissertation submitted in partial satisfaction of the Requirements for the degree of

Doctor of Philosophy

in

Physics

by

Elizabeth Ellen Gire

Committee in charge:

Professor Barbara Jones, Chair
Professor Charles De Leone
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2007

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Chair

University of California, San Diego

2007

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ABSTRACT OF THE DISSERTATION

Between the Poles: Locating Physics Majors in the Expert-Novice Continuum

by

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Professor Barbara Jones, Chair

Expert-novice comparisons have been a productive research tool for investigating many aspect of physics education, including physics conceptions, views about physics, and problem solving activities. These comparisons have typically focused on differences between introductory physics students and physics professor. This thesis examines undergraduate physics majors, who have an intermediate amount of experience studying physics. Known expert-novice distinctions are used to characterize physics majors' views about science and problem solving activities. Views about science are measured with the Colorado Learning Attitudes about Science Survey. Follow-up interviews allowed students to elaborate on their responses to the survey and informed the interpretation of the survey data. During the interviews, students were asked to solve two physics problems. The students' approaches to these problems and their problem solving heuristics are characterized using a scheme developed from known expert-novice differences. It was found that undergraduate physics majors' have many views and problem solving abilities that are similar to those of experts. The implications for teaching physics and physics education research are discussed.

Chapter 1: Introduction

Expert-novice comparisons are a natural way of studying learning. Learning, especially formal classroom learning, can be thought of as a transformation to a more expert-like cognitive state. This state could be defined as having more knowledge about something or using new ways of thinking that are more expert-like. This view of learning suggests that it is important to describe what experts know or how they think so that teaching can be focused on helping students change from their more novice-like cognitive states to more expert-like cognitive states. Having additional descriptions of what students know and how they think is even more useful. Knowing how students differ from experts allows for teaching techniques to be more specifically targeted. For example, research on students' pre-instructional ideas about forces has led to curricula that help students develop Newtonian ideas about forces [1]. This view of learning does not assume that expertise can be achieved in a single course or even at the end of undergraduate study. Rather, it is a continual process of transformation and refinement.

Physics education researchers have embraced this way of thinking about learning and teaching [2]. Much research in the field has focused on describing how and what students think, including their conceptions of physics ideas, their views about the nature of physics knowledge, their views about learning physics, and their problem solving practices. Early research in all these areas focused on comparisons between experts and novices with widely different experience levels. Novices are typically introductory physics students or K-12 science students, few of whom intend to pursue careers in physics. At the other extreme, experts are typically practicing physicists, usually also instructors. However, these expert-novice comparisons exclude a description of intermediate stages of expertise.

Recently, in the area of student conceptions, attention is shifting to students with experience studying physics and who are studying more advanced physics topics [3-12]. Research in student conceptions is expanding to include students with strong commitments to studying physics - many of these students are planning to pursue careers in physics or closely related fields. This thesis continues this trend by focusing on undergraduate physics majors.

Undergraduate physics majors are often viewed by professors as the next generation of physicists. During undergraduate study, physics majors learn about ideas and acquire skills that are important in their development as physicists. Their courses are centered on physical laws and theories, laboratory skills for investigating physical phenomena, and problem solving skills (both analytical and numerical). Other cultural aspects of the discipline (like the historical development of physics ideas, how knowledge is created within the discipline, how physicists interact with each other professionally, and how to learn physics) are important but more peripheral parts of the undergraduate curriculum.

In this thesis, undergraduate physics majors are placed within the expert-novice framework established in previous research. The goal is to determine the extent to which physics majors are like introductory physics students and how they are like physics professors. Two aspects of physics majors' thinking are examined: their views about physics knowledge and their problem solving abilities.

The students' views about physics knowledge were surveyed using a validated, Likert-scale survey instrument – the Colorado Learning Attitudes about Science Survey (CLASS) [13]. Students' responses to the survey were supported by follow-up interviews. Also during these interviews, students were observed solving problems and asked to discuss their general problem solving practices. Two aspects of the students' problem solving activities were analyzed. First, the students' use of physical principles was examined using known expert-novice differences in knowledge organization. Second, the students' use of heuristics was analyzed. The frequency, circumstances, and ease with which different heuristics were used was described.

A preliminary clarification of terminology is needed. The terms attitudes, beliefs, and views have all been used in PER to describe students' ideas about physics knowledge (its nature and origin), learning physics, and solving physics problems. These ideas are related to the amount of effort students are willing to put forth in learning physics, their motivations for engaging in certain learning/problem solving activities, and their personal interest in physics. In psychology, the term attitude is used to describe a construct that represents a person's like or dislike for something (i.e. "I enjoy solving physics problems" – CLASS Item #25) [14]. Similarly, the term belief is used to describe a psychological state in which a person is convinced of the truth of a proposition (i.e. "Knowledge in physics consists of many disconnected topics" – CLASS Item #6) [15]. Attitudes and beliefs are fundamentally connected, and the CLASS probes both. In the CLASS, attitudes and beliefs are convolved with students' expectations ("I do not expect physics equations to help my understanding of the ideas; they are just for doing calculations" – CLASS Item #13). Therefore, no attempt will be made to distinguish between them in this study. The term "views" will be used to encompass attitudes, beliefs and expectations about physics knowledge and learning physics.

The term "heuristics" has different meanings in different fields of study. In this work, the term heuristic will be used in the spirit of Polya [16] as a "rule of thumb". Heuristics will be used to describe problem solving techniques that work well in most circumstances but do not guarantee a solution and may not outline the entire solution path ("strategy" might be a more appropriate term in that case). Visualization and dimensional analysis are examples of problem solving heuristics that will be examined.

Heuristics, techniques, and strategies will also be distinguished from solution approaches. The term "solution approach" will be used to describe the physical principles used in a solution. For example, using kinematical relationships or energy conservation to solve a problem are two examples of solution approaches.

This thesis is structured as follows. Chapter 2 presents a literature review of previous work that has informed and influenced the present study. This research includes studies focused on physics majors, student attitudes and beliefs, and expert-novice differences in problem solving. Chapter 3 outlines the quantitative and qualitative methods used to probe the views and problem solving activities of the study participants.

The results of this study are reported in the next four chapters. In Chapter 4, the survey results are presented and the implications for how physics majors' views develop in undergraduate study are discussed. Students' overall survey scores are discussed, as well as specific views probed by individual survey items and small groups of survey items. Overall, physics majors enter the university with relatively sophisticated ideas about the nature of physics knowledge, and this level of sophistication does not change very much during undergraduate study. In Chapter 5, the criteria used to invite students to be interviewed are presented, and the students included in the final interview data set are introduced. As part of this discussion, the relationship between course grades and survey scores is examined. No correlation is found between students survey score and their course grades. Chapters 6 and 7 present data gathered during the interviews. In Chapter 6, the solution approaches used and discussed by the students are characterized as being expert-like or novice-like. The framework used in making these characterizations is presented. The students' solution approaches have implications for the knowledge organization and problem solving processes of physics majors. Overall, physics majors are found to have similar values as physics professors in terms of the solution approaches they prefer, but their use of physical principles in their solutions is influenced by the order in which physics ideas are taught. Chapter 7 presents evidence of the interview participants' problem solving heuristics. These heuristics are discussed in terms of the circumstances in which they are used, the role they play in the students' solutions, and the students' proficiency in using them. Physics majors are observed to be comfortable using some heuristics more than other, and discuss the circumstances in which they engage in plug-n-chug types of activities.

Another trend in PER is a shift toward thinking about student conceptions from a theoretical perspective of cognitive resources, as opposed to unitary conceptions [17]. A unitary conceptions perspective views students as holding stable ideas that may be correct or incorrect – in the later case they are misconceptions that should be replaced by expert conceptions. In the resources perspective, students are viewed as having general, context-independent conceptions that can be applied productively or unproductively in different contexts. For example, most people have a cognitive resource that "more effort leads to more result". This can be applied productively in thinking about the relationship between force and acceleration ("more force equals greater acceleration", i.e. Newton's 2nd Law), or unproductively from a (scientific perspective) in thinking about the relationship between force and velocity ("more force results in more velocity"). One of the major differences between these two theoretical perspectives is that cognitive resources suggests students have ways of thinking that they can learn to use productively to build expert-like understanding. It also suggests that context is important; students characterized as novices in one context may be more expert-like if the context changes. The results of this thesis suggest that physics majors have many sophisticated views and problem solving abilities that can be used as resources for developing greater expertise.

Chapter 2: Research Background

The goal of this thesis is to describe the intermediate level of physics majors' expertise in the areas of students' views about physics and students' problem solving abilities. This chapter will outline the research that has shaped and informed the present study. It will begin with a summary of education research that has focused on physics majors. This work includes studies of student conceptions of particular physics topics and studies about why students choose to pursue physics as a major. This will be followed by a discussion of the research on students' attitudes and epistemological beliefs about physics knowledge and learning physics. This research has focused on the identification of specific attitudes and beliefs that affect learning and the assessment of students' attitudes and beliefs. Survey instruments that have been developed to characterize the attitudes and beliefs of groups of students will be summarized, and will end with a discussion of the CLASS, the survey instrument used in this study. Then there will be a discussion of research in problem solving, specifically research that has focused on identifying differences between expert and novice problem solvers.

Research on Physics Majors

Little empirical educational research has focused specifically on physics majors. Much of the early work in PER has focused on introductory physics courses, where the numbers of students are substantially larger and where many students have serious difficulties in learning physics [1, 18-24] (for a review see McDermott & Redish [25]). Recently, however, there has been an increased interest in studying students' conceptions of more advanced physics topics, such as quantum mechanics, thermal physics, and special relativity although no work has been done in the area of Lagrangian mechanics [3, 4, 6-9]. These topics are typically taught in upper level courses for physics majors.

Research on physics majors has also focused on why students choose to major in physics. This line of research addresses rising concerns among physics departments of low enrollment in undergraduate physic programs [26-28]. Vazquez-Abad, Winer & Derome [29] conducted a study at the University of Montreal that investigated student persistence in the physics program. They found that those who persisted and those who dropped out differed in their self-perceived knowledge and skills and in their confidence in finishing the program.

Seymour and Hewitt [30] made similar conclusions in their book *Talking About Leaving: Why Undergraduates Leave the Sciences*. In this study conducted over three years at seven universities, researchers interviewed students from the science, technology, engineering and mathematics (STEM) disciplines, about half of whom had switched out of their STEM major before their senior years. They concluded that switchers and non-switchers did not differ in performance or behavior. They found that what distinguished non-switchers from switchers was the development of coping strategies and attitudes, which included competence, confidence, persistence, assertiveness, having a support system of peers, having a strong interest in the discipline, and having a strong interest in the targeted career. The authors discuss gender differences in student persistence, especially of the role of mentoring in retaining female STEM students.

Tobias' [31] *They're Not Dumb They're Different: Stalking the Second Tier* is a study that describes the experiences of students who abandon science for other disciplines. Tobias asked post-baccalaureate students with substantial high school preparation and had taken a least one college calculus course to audit a college chemistry or calculus-based physics course. These students were asked to report their experiences, especially aspects of the course that were difficult. Tobias found that these students were turned off by the competitive culture of these "weeder" courses and the emphasis of computational skills over conceptual understanding. She makes a several recommendations aimed at retaining these students who might have otherwise pursued STEM careers.

Research on Attitudes and Beliefs

Since the early 1980's, students' attitudes and beliefs have been recognized as important factors in students' educational experiences. As described in the preceding section, some attitudes and beliefs affect students' willingness to continue in science programs (i.e. confidence in one's abilities and personal interest). Other attitudes and beliefs have been found to impact students' performance in college science classes [32-34].

Lin [35] conducted an informal study of introductory physics students at the Massachusetts Institute of Technology and found a mismatch in how students and teachers approach physics courses. He concluded that the way students study is determined by assigned tasks (i.e. problem sets and exams) rather than the goals set by the instructor (i.e. a deep understanding of physics and different ways of thinking). This mismatch is attributed to a difference in focus: teachers are focused on the long term goal of deep understanding while students are focused on the short term goal of minimizing the time spent on assignments while doing enough to pass exams. Some of the students' attitudes about problem solving heuristics were identified (preferring one-step solutions, random searches for solutions, and pattern-matched solutions; having a dislike of working symbolically). While many students strongly prefer to have explanatory comments in the instructors' solutions, they prefer to not include any explanation other than equations in their own solutions. The students reported that their use of course textbooks was strongly guided by the problems assigned for homework. Generally, Lin found that time is a major concern among introductory physics students and that their study habits, problem solving, and attitudes are shaped by considerations of time-efficiency.

Hammer [36] interviewed several introductory physics students and found that students can be characterized as having beliefs about physics knowledge and learning physics, and that these beliefs are connected to their problem solving and study habits.

He identified three dimensions of beliefs: the content of physics knowledge (formulas vs. concepts), the structure of physics knowledge (isolated pieces vs. single coherent structure), and learning physics (receiving information vs. actively reconstructing one's own understanding). He found that students who believed that physics knowledge consists of interconnected concepts that can be learned independently without relying on the course instructor studied in a different way than students who believed that physics knowledge consists of discreet facts that come from the instructor.

Elby [37] conducted a survey of introductory physics students that distinguished students' epistemological beliefs about learning and understanding physics from their more course-specific beliefs about what is required to achieve high grades. The goal of this study was to determine if epistemological beliefs alone can account for students studying in ways that a physicist would consider unproductive. Elby concluded that although naïve epistemological beliefs can explain this behavior in some cases, some students engage in rote studying despite having beliefs that this will not lead to deep understanding. He found that students perceive "studying to earn high grades" and "studying to achieve a deep understanding of physics" as significantly different activities. This study supports a case study of an introductory physics student "Ellen" [38], whose initial approach to studying physics was to try to make sense out of the material and integrate it with her own intuitions. A few weeks into a semester-long introductory physics course, she found that she could not use this approach and keep up with the pace of the course. In the end, she changed to a more time-efficient approach, but was frustrated when she could not reach her own understanding of the material.

Current theoretical research on epistemological beliefs looks at these beliefs from a cognitive resources perspective. Hammer and Elby [17, 39] have suggested that identifying students as holding stable beliefs that are either productive or unproductive may be an incomplete description of these beliefs and does not easily suggest a way to change students' beliefs. Instead, they propose thinking about students' as having general ideas about the nature of knowledge ("epistemological resources") that can be applied to different situations in ways that can be productive or unproductive. For example, one epistemological resource might be thinking of knowledge as tentative. This may be a productive way for theoretical physicists to think about the applicability the Standard Model, because they understand that it applicable in a specific range of conditions and may be discarded if experimental evidence is accumulated that supports a different model. However, for introductory students solving textbook problems, thinking about the applicability of Newton's Law as tentative may be unproductive for learning.

Hammer and Elby have identified some epistemological resources for sources of knowledge (i.e. fabricated, inferred, propagated, etc), epistemological activities (checking, accumulation, formation), forms of knowledge (story, rule, fact, game) and stance towards knowledge (acceptance, understanding, puzzlement). In the case of physics students, these epistemological resources are applied to physics knowledge in either productive or unproductive ways. This resources perspective proposes that students have cognitive resources available to them for learning and using physics knowledge in productive ways. The advantage of looking at epistemological beliefs in this way is that it suggests that instruction can help students learn to use these epistemological resources in a way that is productive for learning physics [17, 40, 41].

Attitude Surveys

There have been many pencil-and-paper surveys developed for identifying the attitudes and beliefs about science and physics. One of the earliest surveys was the Epistemological Questionnaire (EQ) [42]. This survey probed five dimensions of epistemological beliefs about science: complexity of knowledge (simple vs. complex), source of knowledge (an omniscient authority vs. derived from reason), certainty of knowledge (certain vs. tentative), ability to learn physics (innate ability vs. acquired ability), and time-scale of learning (it's either quick or not-at-all vs. it can take some time). The EQ has not been widely used to measure the epistemological beliefs of physics students, but prompted the development of other physics specific surveys.

The View about Science Survey (VASS) [34, 43] was also developed to probe students epistemological beliefs about science. The survey focuses on two dimensions of beliefs: a scientific dimension (the structure, methodology, and validity of scientific knowledge) and a cognitive dimension (learnability, the role of critical thinking, and personal relevance). In designing the survey, the authors developed a Contrasting Alternatives Design, where each item presents an incomplete statement followed by two contrasting phrases that completes the statements – an expert alternative and a novice alternative. These characterizations were based on the views that the authors judged to be held by scientists and educators at large and that were held by the majority of 50 high school teachers and 27 university professors. The students are asked to report the extent to which they agree with each of the contrasting statements on an eight point scale. Each student is then profiled as Expert, High Transitional, Low Transitional and Folk based on the distribution of expert, mixed or folk responses given.

This survey has been used to show that students do not hold consistent views about any of the dimensions probed by the survey. Each student holds a mixture of folk, mixed and expert views in each of these dimensions. Halloun also looked at trends between VASS profile and course grade and also between VASS profile and conceptual learning as measured by the Force Concept Inventory (FCI) [20]. VASS responses, course grades, and FCI scores (pre and post) were collected from three levels of college physics courses: a calculus-based course (n=128), an algebra-based course (n=77), and two elementary courses for non-science majors (n=121). 58% of the students who were characterized as Expert received a course grade of A or B, while only 28% of the students characterized as Folk received these high grades. Furthermore, none of the Expert students failed. Similar trends were found for FCI score. 65% of students with Expert profiles made high normalized gains ($g \geq 0.52$), whereas only 20% of students with Folk profiles made high normalized gains. From this data, the authors concluded that VASS profile correlates with course achievement and conceptual learning.

The Maryland Physics Expectations survey (MPEX) [18] is a Likert-scale survey designed to probe students' attitudes and beliefs about science, but in contrast to the EQ and the VASS, the survey items are discussed in the context of a physics course and it probes students' course-specific expectations. The survey consists of 34 statements, and students are asked to rank their level of agreement with each statement on a five point Likert scale. The students responses are then compared to the "expert response" - a consensus of 19 university faculty that demonstrated at least a moderate interest in the results of PER. The survey probes six dimensions of attitudes, beliefs and expectations: independence, coherence, concepts, the link between physics and the real world, the link between physics and math, and the amount of effort students expect to put into their physics courses.

One of the major results of studies using the MPEX is that students' attitudes typically become more novice-like between the beginning and end of their introductory physics courses. One explanation for this effect may be that students are optimistic at the beginning of the course about what they expect their behavior to be, while at the end of the course they may be focused on earning high grades rather than studying for deep understanding [38]. Furthermore, in calibrating the survey, five groups with different amounts of experience studying physics were surveyed: introductory physics students (engineers), the US Physics Olympic Team, high school teachers, college and university teachers, and the "expert" group of college and university teachers. It was found that the trend in average MPEX score followed the level of sophistication expected for each of these groups [18].

The Epistemological Beliefs Assessment for Physics Science (EBAPS) [44] was developed to probe the epistemological stances of students in introductory physical sciences (physics, chemistry, physics science). The EBAPS was specifically designed to accommodate for students' beliefs that are context dependent, and to distinguish between students' epistemological beliefs, course expectations, and goals.

The Colorado Learning Attitudes about Science Survey is the most recent survey designed to measure students' attitudes and beliefs in the specific context of physics [13]. It is a 42 item, Likert-scale survey based largely on the MPEX, but with some significant differences. First, the survey items were simplified so that each item focuses on one attitude or belief. Second, the survey does not probe students' expectations about their courses. Interviews with students revealed that students think of the definition of physics as describing three contexts: the physics that describes nature, the discipline of physics, and physics courses. The CLASS items were written so that word "physics" is used as the physics that describes nature, although there is overlap between this meaning and the others (i.e. students think of solving physics problems mainly in the context of a physics course). This wording allows for the survey to be administered to students in a variety of physics courses and many of the items can be answered by people who have not taken any physics courses.

Like the MPEX, the survey is scored by comparing student responses to an "expert" response. The expert response was generated by a concurrence of 16 university faculty. The items that did not achieve 100% concurrence were either reworded or excluded from scoring. Of the 42 items, only 36 are scored. Most of the items that are not scored have to do with learning styles, and it is unsurprising that there is some variation in how experts respond to these items.

Subsets of items have been identified as CLASS Categories. These categories were formed by a factor analysis of student responses, looking for coherences in how students respond to the survey items. The factors identified in the analysis were then modified by the researchers in order to increase the conceptual coherence of the categories. The categories address topics like the conceptual nature of physics knowledge, students' confidence in problem solving, problem solving habits, link between physics knowledge and the real world, and personal interest.

The CLASS has been used to correlate students' attitudes with other learning outcomes [41, 45]. It was found that students who make larger commitments to studying physics are those who recognize physics as being more relevant to their own lives. It has also been seen that students' attitudes are connected to conceptual learning gains as measured by the Force and Motion Conceptual Evaluation (FMCE) [46]. As in studies of attitudinal shifts using MPEX, it has been seen with CLASS that students' overall survey score decreases between pre- and post-testing in typical large introductory physics courses, and overall survey scores show small increases in courses that are specifically aimed at improving students beliefs [40, 41]. The CLASS has also been used to show that students whose overall CLASS score increased between the beginning and end of a semester-long introductory physics course also rated their personal interest in physics as having increased. This increase in interest was found to be related to students' epistemological beliefs. The leading reason for increased interest was the connection between physics knowledge and the real world [45].

A major question in the validity of epistemological surveys is "Do students really answer what they believe, or do they report what they think their professors want them to say?" To investigate this, Adams, et al. [13] asked students to respond with their own beliefs and with how they think their physics professors would respond. The results indicated that the students were able to distinguish between their own beliefs and what they think the "expert response" is, and that students are able to accurately identify expert beliefs. It was also suggested, though there was not enough data to perform a statistical comparison, that students' responses to CLASS typically are close to their own beliefs.

Problem Solving Differences between Experts and Novices

A productive way of studying problem solving in physics has been to compare expert and novice problem solvers. Expert/novice studies have generally focused on identifying differences in knowledge organization and problem solving behavior. This work was built on work that had been done in the area of chess expertise [47, 48]. Studies of expert and novice chess players revealed that chess experts were able to retrieve information from long term memory in associated groups called chunks. This ability to chunk information has been viewed as evidence that experts and novices organize information in memory differently, and suggested that this difference in knowledge organization was in part responsible for differences in problem solving expertise.

In 1978, Simon and Simon examined expert-novice problem solving differences in the domain of physics (specifically, motion in a straight line). The novice was described as someone who had taken a college level physics course many years previously and had adequate algebra skills, while the expert had strong mathematical skills and extensive experience solving physics problems. The problem solvers were asked to think aloud while solving the problems, and their solutions were analyzed using a protocol analysis [49]. Simon and Simon found that the expert tended to use a working forward strategy to find solutions, while novice tended to use a strategy of working backwards. The authors also define "physics intuition" as a cognitive representation of a problem that includes physics entities (like force, energy, etc.) and focuses on causal relationships between components of the situation.

Larkin [50] conducted a similar study based on think-aloud problem solving and protocol analysis. In this study, two experts and one novice were asked to solve five mechanics problems, and some general differences in their protocols were observed. Larkin found that the experts tended to start with a qualitative analysis (reformulating the problem to a representation that is an intermediate between the real objects involved in the problem and the physical principles needed to solve the problem). Experts also tended to think of physical principles and relations in chunks (retrieved in short time periods). Larkin then tried to teach her introductory E&M students to use similar procedures – performing a qualitative analysis and studying for chunking. Students who were instructed to perform qualitative analyses and to associate physical relations in chunks had greater success solving problems, tended to use more diagrams, and demonstrated more planning in their solutions.

Larkin [51] proposed that when faced with a physics problem, novices construct a mental representation called a naïve representation, that involves familiar, real-world objects and is distant from physical principles (also have a tree structure/single inference source, presumably related to time evolution, and have diffused properties of entities). In addition to these naïve representations, experts construct a physical representation that contains physical entities (force, energy, etc.) and are closely tied to physical principles (also have a graph structure/redundant inference sources, and entities have localized properties). Both of these representations are separate from mathematical representations (i.e. equations).

The issue of forward-working or backward-working problem solving strategies has not been settled. Priest and Lindsay [52] performed a series of problem solving experiments in which introductory physics students (novices) and doctoral physics students (experts) were asked to provide written solutions to six mechanics problems, and then provide written solution plans (though not actually solve) to two additional mechanics problems. The researcher found that these novices chose forward thinking strategies just as often as the experts. The experts solved the problems correctly more often than the novices, and were able to make complete plans more often than novices.

Meanwhile, research on expert-novice differences in knowledge organization continued. Chi, Feltovich and Glaser [53] performed a series of experiments that looked at how experts and novices categorized physics problems and how these categorizations were related to problem solutions and knowledge organization. They asked novice (introductory physics students) and experts (professors) to sort some Halliday and Resnick [54] problems based on solution similarity. They found that experts tended to categorize problems based on the physical principles that would be used in the solution, and that novices tended to categorize problem together based on the similarity of the surface features of the problems (i.e. if the problem involved an inclined plane). These experiments led the authors to conclude that expert knowledge is organized in a hierarchy related to physical principles. Experts construct problem representations based on these physical principles, while novices lack the knowledge organization to do so. Instead, novices focus on surface features when constructing a mental representation of the problem situation.

Hardiman, Dufresne, and Mestre [55] expanded on this work by having experts (n = 10 PhD physicists) and novices (n = 45 introductory physics students) perform problem categorization tasks: (1) experts and novices were given a sample problem and two other solutions and were asked to pick the problem whose solution most closely matched the sample problem, and (2) experts and novices were given two problems and asked if the solutions to the problem were similar and then asked to explain their reasoning. Novices were asked to solve these last two problems so that their problem solving abilities could be determined. The researchers found that the experts tended to categorize problems based on physical principles while the novices tended to categorize problems based on surface features, although the experts were sometimes distracted by surface features and some novices considered physical principles when surface similarity was absent. There was some variation in the degree that novices used physical principles to categorize problems. Students who are better problem solvers also tended to be the students who considered physical principles in problem categorization most frequently.

One criticism of the early work in physics problem solving is that the problems typically chosen for these studies are very familiar to the expert problem solvers, making for an unauthentic problem solving situation. Singh investigated the case where the experts were challenged with a non-standard problem. During 30 minutes interviews, Singh asked 20 physics professors to solve a problem from Halliday & Resnick [54] that is not typical of the problems assigned to students. Singh also solicited solutions from 67 calculus-based introductory physics students. Most students provided written solutions, but several students were interviewed. She found that experts acted a lot like novices in that they had difficulty with initial planning. However, experts almost always visualized the problem globally and thought about the applicability of physical principles. They often searched for useful conservation laws before resorting to other routes. They considered limiting cases and drew analogies with familiar situations, and often with real world scenarios. Novices seldom employed a systematic approach to the problem and rarely examined limiting cases, contemplated the applicability of conservation laws or used analogical reasoning.

Overall, many expert-novice differences in solving physics problems have been identified [2, 56]:

1. **Experts have more domain specific knowledge than novices** [57, 58]

   Experts are aware of more physics ideas and have more solved more physics problems than novices. Increased experience allows experts to use "physical intuition" in their problem solving. Physical intuition is difficult to define, but has been described as representing a problem with a schema of physics entities that intermediate between the surface structure of the problem and the principles used in the solution of the problem. Physical intuition is also related to general solution methods that are borne out of solving many similar problems.

2. **Expert knowledge is richly interconnected; novice knowledge is mostly disconnected/amorphous** [36, 50, 53]

   For experts, concepts are linked to each other. Experts are aware of structural relationships between concepts, and are able to chunk concepts together for increased recall. For novices, physics knowledge is composed of memorized facts that are disconnected from other facts. Teaching techniques that focus on students performing qualitative analyses and associating physical principles in chunks have been shown to increase student problem solving success.

3. **Experts' knowledge is structured hierarchically; novices' knowledge has little hierarchical structure.** [2, 53, 58]

Expert knowledge is organized around physical principles (conservation principles, Newton’s Laws) while novice knowledge is organized around surface features of problem situations (like inclined planes and pulleys). Novices often use external contextual clues (like which chapter in the text the problem came from) to select solution paths.

4. **Experts are more likely to perform a qualitative analysis of a problem than novices.** [50, 51, 59]

   Experts develop an appropriate physical representation (mental model including physics entities like force, velocity, fields, etc.) before beginning computations. Experts are more likely to initially form a productive physical representation than novices – novices are more likely to develop several mental models (including experiential and scientifically false models) and then choose from them.

5. **Experts tend to use more forward-looking, concept-based strategies; novices tend to use backward-looking, means-ends techniques.** [52, 58]

   For multi-step problems, experts have been observed to apply equations in a forward-working order (starting with fundamental relationships and working toward the sought quantity in a logical progression), while novices more often work-backwards, starting with the sought quantity. Experts have been observed to use more means-ends techniques for more difficult problems.

6. **For novices, problem solving tends to use all available mental resources; experts are able to think about problem solving while problem solving.** [60, 61]

   Experts have been observed to plan and monitor their own thinking while solving problems. Novices tend to focus much of their cognitive effort on making computations and have difficulty planning a solution.

7. **Experts are able to check their answers using alternate methods; novices often only have one way of solving the problem.** [60]

   Experts often know many solution paths for a given problem and spontaneously verify an answer by solving a problem more than one way. Novices rarely check answers in this way.

Few studies have probed intermediate levels of problem solving expertise by including more experienced physics majors. One study that did so was conducted by Chi, Feltovich and Glaser [53]. This study was aimed at ascertaining problem solvers' knowledge structures. They asked a senior undergraduate physics major to categorize a set of 20 physics problems and compared the categories generated to those of a physics graduate student (an "expert") and a student who had taken one course in mechanics (a "novice"). The results of the study showed that the expert graduate student's categorizations were primarily based on physical principles ("deep structures"), the novice's were primarily based on surface features ("surface structures"), and the senior physics major used a strategy that considered both physical principles and surface features (as a secondary factor). The authors concluded that this study supports a difference in the knowledge organization of experts and novices. Additionally, this study suggests that studying undergraduate physics majors can yield insight of intermediate stages of expertise.

Summary

The areas of problem solving and epistemological beliefs have received a lot of attention in the PER community. Much of the work done in these areas is focused on making expert-novice comparisons. These comparisons have been explicitly made in examining problem solving processes and knowledge organization. Epistemological surveys judge students' views as favorable or unfavorable based on whether they are aligned with the views of experts. These comparisons have generally been made between introductory physics students and physics professors, two populations with widely different level of experiences studying physics. Very little is known about students with more intermediate amounts of experience, and descriptions of intermediate levels of expertise may lead to better understanding of how expertise is achieved. Studies that have focused on physics majors have been aimed at understanding why students choose to study physics.

Chapter 3: Methods

This thesis aims to describe the intermediate level of expertise of physics majors in two areas of knowledge: the students' views about physics knowledge and their problem solving abilities. These investigations rely on two main sources of data: a large-scale survey using the Colorado Learning Attitudes about Science Survey (CLASS) [60] and interviews with several physics majors. The CLASS is designed to probe the students' attitudes about physics, including their views about the nature of physics knowledge, their problem solving activities, how they study physics, and the role that physics knowledge plays in their everyday lives. The CLASS is a 42 item, Likert-scale survey that can be administered to large numbers of students and analyzed using statistical techniques. However, the survey is not designed for students to elaborate or explain their responses. Interviews are needed to get more detailed portraits of the attitudes and problem solving activities of individual students.

Interviews were conducted with a subset of physics majors who took the CLASS survey. During the interviews, the students discussed their experiences in studying physics and elaborated on their survey responses. They were also asked to solve some physics problems so that their problem solving activities could be observed and discussed. In contrast to the survey data, the number of interviews that could be conducted was limited by the substantial amount of time it takes to analyze each interview. Therefore, the interviews do not yield statistically significant patterns within the physics major. Instead, they provide information about undergraduate physics majors as a group that has an intermediate amount of experience studying physics.

This chapter will begin with a detailed account of how the CLASS survey was administered and analyzed, followed by a discussion of the interviews, including the structure of the interviews, and the analysis of the interview data. The selection of interview participants is discussed in Chapter 5.

CLASS Survey

Administration

The CLASS was administered to 519 students during the 2004-2005 and 2005-2006 academic years at the University of California, San Diego. Many courses were surveyed, including lower-division and upper-division courses for physics majors, a course for first-year physics graduate students, and several sections of an introductory physics course for engineering students (See Table 3-1). The engineering students were surveyed in order to compare physics majors to non-majors with similar high school training in math and science.

The courses for physics majors are small (n~30) and are uniformly taught in a traditional lecture format. The physics department recommends a four-year program of courses [62], and students generally take these courses in the order recommended by the department. Courses that are required for physics majors were surveyed repeatedly

Table 3-1: Courses surveyed, with information about topic covered, which year students typically take course, number of respondents for each year, and academic quarter during which each course was surveyed. For the physics major courses (all, except 2A), same-colored cells indicate a cohort of students who may have been surveyed multiple times.

	# Students	Courses Surveyed	Fall 2004	Winter 2005	Spring 2005	Fall 2005	Winter 2006	Spring 2006
Eng.	378	**2A** *Mechanics for Engineers*	⬛	⬛	⬛			
Year 1	33	**4A** *Newtonian Mechanics*		🟥			🟨 **Pre &Post**	
		4B *Fluids, Waves & Thermo.*			🟥			🟨
Year 2	29	**4C** *Electricity & Magnetism*	🟦					
		4D *Optics, Special Relativity*		🟦				
		4E Quantum Physics			🟦			🟥
Year 3	56	**100A** *Electricity & Magnetism*	🟩					
		100B *Electricity & Magnetism*						
		100C *E&M Elective*			🟩			🟦
		130A Quantum Mechanics			🟩			
Year 4	16	**130B** Quantum Mechanics	🟪					
Grad	7	**200A** Graduate Mechanics	🟫					

in a rotating panel study design [63]. Individual students in different stages of the program were surveyed several times, yielding cross-sectional and short-term longitudinal data.

The surveys were administered in lecture and students recorded their responses on scantrons. An advantage of this approach is that, in yielding lecture time, instructors give implicit (or in some cases explicit) encouragement to participate in the study and to take the survey seriously. We also found that students who chose to volunteer were likely to complete the entire survey. A disadvantage of administering the surveys in class is that lecture time is limited and some instructors are reluctant to yield it. Even if they do, some students are rushed to address all 42 survey items. Only students who attended lecture were invited to take the survey, and no course credit was given for participating in the study.

The survey was administered in each course during the last two weeks of instruction, before the students took their final exams. The only pre-test administered was in the first course of the physics degree program (4A) during the winter quarter 2006 to establish a baseline before students begin the physics program. The survey was administered only once per course in order to avoid effects of sampling the students too often (in the quarter system, a student could be asked to take the survey six times in a single academic year with both pre- and post-testing).

Although many surveys are currently available for measuring students' attitudes about physics [18, 43, 44] the CLASS is convenient for comparing physics students at different stages of degree progress. In making such a comparison, it is important that the survey does not include items that probe the students' expectations of a particular physics course. The CLASS items were designed to use the term "physics" to refer to the physics that describes nature, not to a particular course or the scientific discipline. Although students are likely to be influenced by their current courses in responding to the survey, the wording of the CLASS items allows students to respond more generally about their physics experiences, making it easier to compare students across a range of experience-levels. Furthermore, when calibrating the survey, the "expert" physics professors were asked to respond to the survey items based on their own views (instead of "How would you like your students to answer?"). This framing is useful in trying to make inferences about how novice students develop more expert-like views.

Analysis

The surveys were analyzed using standard techniques for Likert-scale surveys, by comparing a student's response to the "expert" response for a particular survey item. The expert response, determined by Adams, et al., was established by a consensus of 16 physics professors at University of Colorado, Boulder. If the student's response is similar to the "expert" response, then the student's response is scored as "favorable". Each student was assigned an overall survey score based on the percentage of survey items scored as favorable. This score was averaged over students in the same year of study, and ANOVA was used to detect differences between years [64]. Additionally, individual survey items and subsets of survey items were compared across year. For this cross-sectional analysis, if a student completed the survey in multiple courses, only the student's first survey was included to ensure that all years are independent. The Games-Howell test was used for post-hoc comparisons between years [65]. This test is similar to a t-test, but reduces the probability of falsely rejecting the null hypothesis when making multiple comparisons between groups and is appropriate when the groups have unequal variances.

The longitudinal component of the study included students who responded to the survey in multiple samplings over time. These students' first and last survey scores were compared using two-tailed, paired samples t-test. For both the cross-sectional and longitudinal analyses, differences at the $p < 0.05$ level were considered to be significant. Students who had declared non-physics majors were excluded from these analyses, except for the students in the introductory physics course for engineers.

Interviews

Purpose and Goals

Interviews were conducted to complement the CLASS data, and three main research questions were pursued. The first research goal was to a detailed characterizations of some of the students’ specific views about science. Generally, surveys are convenient for characterizing the views of large groups of students, but the information that can be collected with the surveys is constrained. Students are limited in the types and lengths of responses they can give, and there is some variation in the way individual students interpret the survey items. Interviews yield more detailed information about students' views than the survey alone. Interviews also allow the researcher to probe more deeply and broadly about these views: explanations of why certain views are held, types of experiences that contribute to the formation of these views, and the context in which the students respond to the survey items. While many views were discussed during the interviews, only the students' views about plug-n-chug strategies were analyzed in detail.

A second research goal of the interviews is to characterize students' problem solving activities through observations of students solving physics problems. Problem solving is one of the dimensions of the CLASS, and observing the interview participants solving problems provides a complementary data set. While the survey probes general problem solving activities, there is no opportunity for students to distinguish between the activities they use while solving easy problems and those used for difficult problems, or to report differences for different physics topics. Problem solving activities are influenced and often dictated by the specific context of the problem. For example, a student may be more comfortable thinking about real world experiences while solving a mechanics problem than for a quantum mechanics problem, or may only think about real world experiences while solving difficult problems. Using the topics of mechanics as the specific physics context of the interviews and including both easy and difficult problems allows for more detailed characterizations of the students' problem solving activities and makes comparisons with existing problem solving literature more direct.

Two aspects of problem solving were of particular interest. First, the physical principles used by the students in their solutions were probed, and students were asked to discuss alternate solutions. Experts and novices have been identified as having different ways of organizing knowledge, and the students' solution approaches provide some evidence of this organization. Second, the problem solving heuristics used by the students during their solutions were examined. Expert and novice problem solvers are known to use different heuristics for solving problems. Experts tend to use qualitative analysis activities more often than novices, while novices are known to use plug-n-chug strategies. Since physics majors have an intermediate amount of experience, it is expected that they will engage in both types of activities, though the extent and circumstances under which different activities are used is unknown.

A third research goal is to determine if the interview participants considered themselves to be physicists. One function of undergraduate physics programs is to develop physicists. This development not only includes learning physics content and techniques, but also to become familiar with the culture of physics and the ideas about the nature of physics knowledge that are accepted by the community of practicing physicists. While the details of the students' responses are not reported at this time, this line of questioning has interesting implications for the patterns seen in the survey results.

Description of the Interviews

Eight physics majors agreed to be interviewed. The interviews were about 90 minutes in duration and involved four major lines of questioning: the students' backgrounds studying physics and their reasons for declaring a physics major; students solving two physics problems and commenting on sample solutions to those problems; students elaborating on their responses to the CLASS survey; and students discussing whether they consider themselves to be physicists as well as how they might identify someone else as a physicist. Most of the interviews proceeded in the order described, however some students elected to discuss their survey responses before solving the physics problems.

The interviews were semi-structured, meaning that the same general questions were asked in all the interviews, but the interviewer was free to pursue lines of questioning to accommodate for the specific circumstances of each student or that allowed students to elaborate on their reasoning. This flexibility means that there is a certain amount of variation between interviews. In order to compare responses from individual students, it is important that the responses be considered in the context of the specific interview. This protocol structure was chosen in consideration of the exploratory, generative nature of the study [66].

Three types of data were collected during the interview – audio, video and text. The verbalizations made by the students were audio recorded and later transcribed. Video recordings of the students were taken specifically to preserve the time sequence of what the students wrote while solving the two physics problems. To capture this information, the camera was placed above the students and pointed downward at the desktop. Only the students' papers, writing arms, and (in some cases) the tops of their heads are in the camera's field of view. Notes were generated based on the video recordings of the problem solving portion of the interview in order to supplement the transcripts of the audio recordings. The students generated two pieces of written work – their written solutions to the two physics problems and their written responses to the CLASS survey.

Analysis of Interviews

The interviews were analyzed using an approach that involved several iterations of coding. Later iterations of coding were informed by previous research on the differences between expert and novice problem solvers. A coding scheme was not developed prior to conducting the interviews, and coding began with an exploratory coding of interview transcripts and field notes [67]. The four main interview sections (background, problem solving, survey discussion and identity) were separated, and independent, general codes were used for each section. The background and identity sections were the shortest and most uniform parts of the interview. The problem solving section had the most variation across students. The first pass through the problem solving section involved descriptive, indexical codes that flagged the content of the discussions and some of the problem solving activities that were taking place. After the initial phase of coding, it became clear that the interviews addressed some aspects of problem solving that had been identified in comparison studies of expert and novice problem solvers. Specifically, the physical principles used and discussed by the students were examined, as well as the problem solving heuristics used by the students during their solutions. Later codes became more focused on evidence that addressed these issues. The codes developed for analysi

In order to characterize the students' solution approaches, a survey of expert-novice comparison studies and review articles was conducted, and a list of expert-novice differences was generated. This list was presented in detail in Chapter 2 and is summarized here:

1. Experts have more domain specific knowledge than novices.
2. Expert knowledge is richly interconnected; novice knowledge is mostly disconnected/amorphous.
3. Experts' knowledge is structured hierarchically according to physical principles; novices' knowledge does not appear to be structured in this way.
4. Experts are more likely to perform a qualitative analysis of a problem than novices.
5. Experts tend to use more forward-looking, concept-based strategies; novices tend to use backward-looking, means-ends techniques.
6. For novices, problem solving tends to use all available mental resources; experts are able to think about problem solving while problem solving.
7. Experts are able to check their answers using alternate methods; novices often only have one way of solving the problem.

These differences were then considered in the specific context of these interviews, and a new list was generated that contained expert-like and novice-like solution approaches that could be identified and coded in the interview transcripts. The details of this framework are presented Chapter 6. Once these approaches were identified for each student, they were considered across students to determine how physics majors are expert-like and how they are novice-like in their solution approaches. This analysis of students' solutions was generally modeled after the approach taken by Dancy & Henderson to develop a scheme for characterizing instructors' beliefs about teaching and their teaching practices as either traditional or alternative [68].

A literature review was also conducted to identify heuristics that are known to be used to solve physics problems. These heuristics include visualization, problem categorization, making simplifying assumptions, making analogies to familiar situations, considering limiting cases, performing a dimensional analysis, and equation hunting. Specific instances of students' using these heuristics during the interviews were identified. Although most of these heuristics are known to be valued by experts (with equation hunting being a notable exception), the students' uses of these heuristics are not discussed in terms of an expert-novice framework. Instead, the circumstances under which these heuristics were used and the students' apparent proficiency in using them will be discussed. This analysis was modeled after Singh analysis of expert and novice problem solvers [57].

Chapter 4: Views about Science as Measure by the CLASS

In this chapter, the views of undergraduate physics majors in various stages of degree progress are examined. Expert-novice comparisons show that the views of introductory physics students can be quite different from those of physicists. However, these end-point comparisons do not address questions about how expertise is achieved. It has been demonstrated that students in introductory courses can develop more expert-like views when discussion of epistemological issues is explicit and integrated into the curriculum [17, 69], but typically students' views become less expert-like during introductory courses. Most studies have focused on the views of introductory students and physics faculty, and little has been reported about the views of students in higher level physics courses. In understanding the development of expert-like views, an important question remains: to what extent do students' views change to become more expert-like and to what extent are pre-existing expert-like views selected for during undergraduate study?

In this study, the views of undergraduate physics majors at various stages of degree progress are surveyed using the Colorado Learning Attitudes about Science Survey. The development of student views is probed by looking for differences at different academic stages.. The relative expertise of physics majors is compared with that of non-majors and graduate students in physics. Stages in the development of physics students' epistemological stances are proposed and discussed, including a possible connection between CLASS survey response and self-identification as a physicist.

Methods

Undergraduates at the University of California, San Diego (n=519) were surveyed in a rotating panel study, yielding both a cross-sectional data set and a longitudinal data set. Students were surveyed at the end of their physics courses, and physics majors were specifically targeted. First year graduate students in physics and engineering majors in an introductory physics course were also surveyed for comparison purposes. The surveys were scored in the standard way [13], and overall scores, CLASS categories, and individual survey items were analyzed statistically. The details of how and when the survey was administered and the techniques used to analyze the survey data are discussed in Chapter 3. The surveys were also scored using a polarization binning that preserves the strength of the students' responses. A detailed account of this analysis is included in the discussion section of this chapter.

Results

Overall Score

Figure 4-1 shows the average number of favorable responses from students in each year of the physics major, the introductory course for engineering students (Eng), and the graduate course (200A). Our classification of “Year” is based on the department's suggested timing and sequence of courses for physics majors. A student’s response is considered favorable if it is similar to the expert response. For example, if the expert response is “Agree”, than a student response of either “Agree’’ or “Strongly Agree” would be scored as favorable.

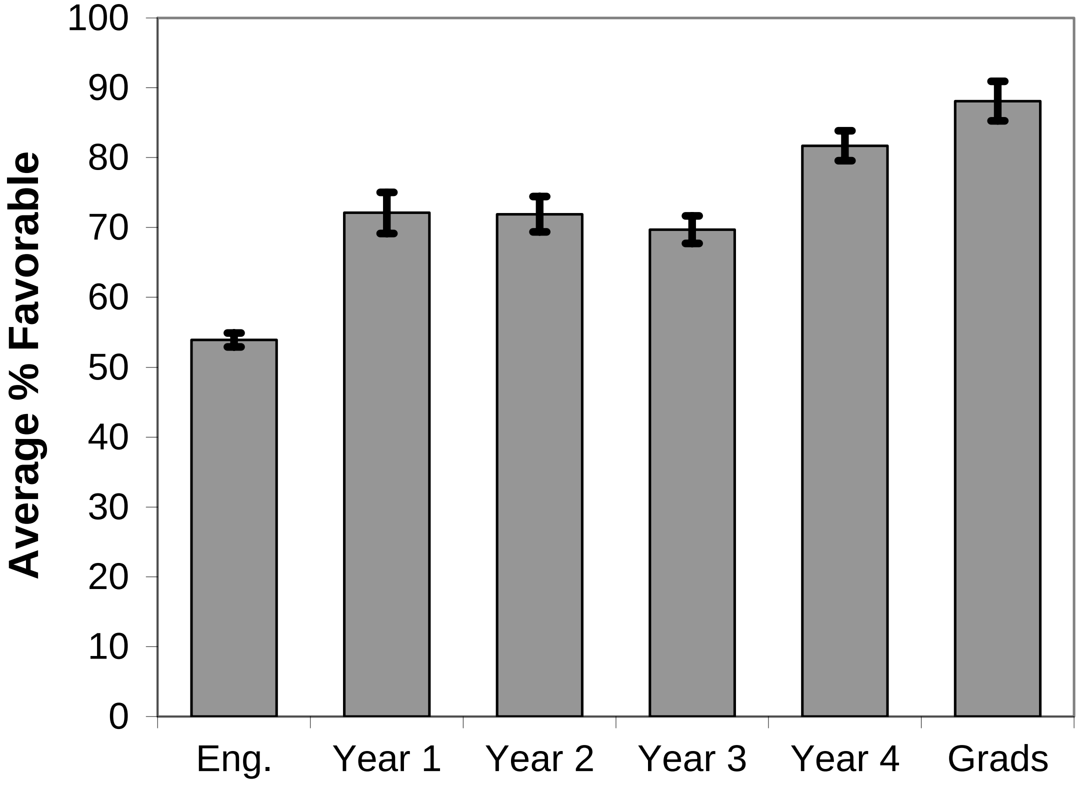


Figure 4-1: Average overall CLASS score by Year. Error bars indicate the standard deviation of the mean.

Table 4-1 shows the courses included in each year, as well as the number of respondents. An analysis of variance indicates statistically significant differences between the average number of favorable responses of these groups, F(5,513)=26.17,

$p < 0.001$. Games-Howell post-hoc testing, summarized in Table 4-2, indicates that the engineering students are statistically different from all years of physics majors and graduate students (Grads). There are no statistically significant differences between Years 1, 2 and 3, or between Year 4 and Grads. Furthermore, students in Years 1, 2, and 4 are not significantly different from each other; however, there is a significant statistical difference between Year 3 and Year 4.

Table 4-1: Average overall CLASS score, with courses surveyed, number of respondents in each year and standard deviation

Course *(Topic)*	**Year**	**N (year)**	**Average % Fav.**	**St. Dev.**
2A *(Mechanics for Engineers)*	Eng.	378	53.9	19.3
4A *(Newtonian Mechanics)* 4B *(Fluids, Waves & Thermo.)*	1	33	72.1	16.9
4C *(E&M)* 4D *(Optics, Special Relativity)* 4E *(Quantum Physics)*	2	29	71.9	13.6
100A *(E&M)* 100B *(E&M)* 100C *(E&M Elective)* 130A *(Quantum Mechanics)*	3	56	69.7	14.7
130B *(Quantum Mechanics)*	4	16	81.7	8.5
200A *(Graduate Mechanics)*	Grad	7	88.1	7.5

Table 4-2: Summary of Games-Howell results for analysis of overall CLASS score

Group i	Group j	Difference in Average % Favorable (i-j)	P
Eng	Year 1	-6.56*	<.001
	Year 2	-7.17*	<.001
	Year 3	-5.87*	<.001
	Year 4	-9.84*	<.001
	Grads	-12.30*	<.001
Year 1	Year 2	-0.62	0.998
	Year 3	0.68	0.994
	Year 4	-3.28	0.141
	Grads	-5.74*	0.009
Year 2	Year 3	1.3	0.868
	Year 4	-2.66	0.239
	Grads	-5.13*	0.016
Year 3	Year 4	-3.96*	0.005
	Grads	-6.43*	0.002
Year 4	Grads	-2.46	0.422

The low number of students sampled in Year 4 raises concerns that perhaps this is not a representative sample of students. To address this issue, two grade comparisons were made. Since CLASS score has not been shown to correlate significantly with grades, course grades and grade point averages were used toindependently characterize the Year 4 sample. First, the course grades of the survey respondents were compared to the grades of physics majors in the same course who did not take the survey. In the Year 4 course sampled, 28 physics majors were enrolled and 16 of those students responded to the survey. A Welch test showed that the distributions of course grades for the respondents and non-respondents were the same at a level of p=0.93. Figure 4-2 shows histrograms of both distributions. Second, the overall GPAs of the Year 4 respondents were compared to the overall GPAs of the Year 3 respondents. Histograms are shown in Figure 4-3. A Welch test showed that

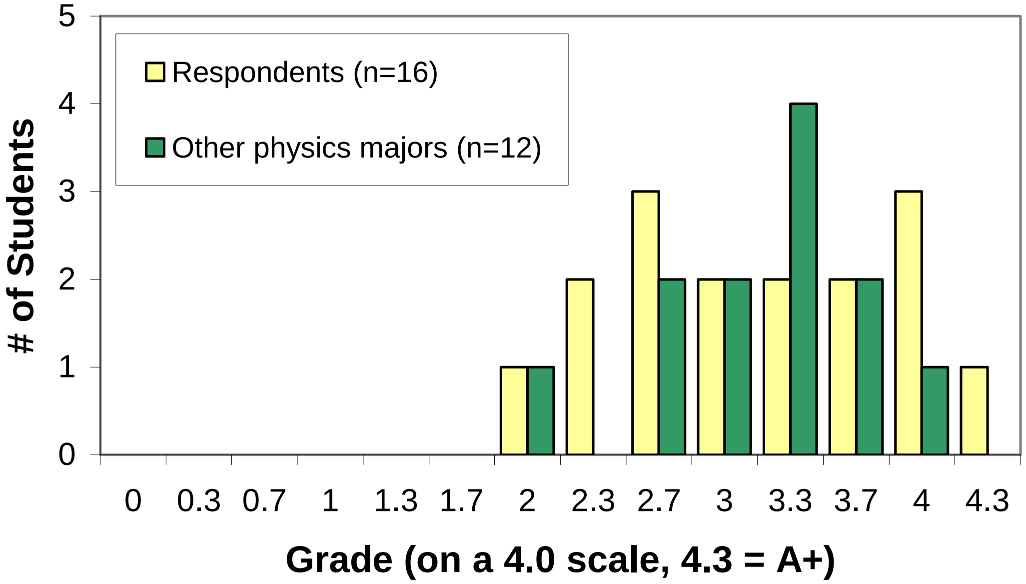


Figure 4-2: Distribution of course grades for Year 4 respondents and non-respondents

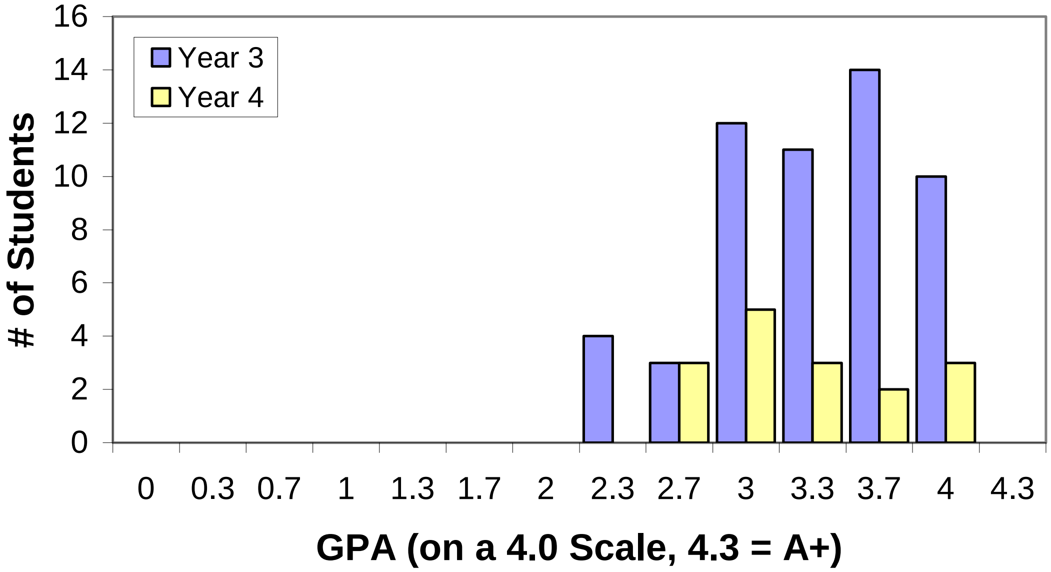


Figure 4-3: Distributions of grade point averages for Year 3 and Year 4 respondents

the distributions are the same at a p=0.43 level. These comparisons suggest that the students sampled in Year 4 represent the Year 4 physics majors reasonably well and that the Year 3 and Year 4 students are not intrinsically different populations of students.

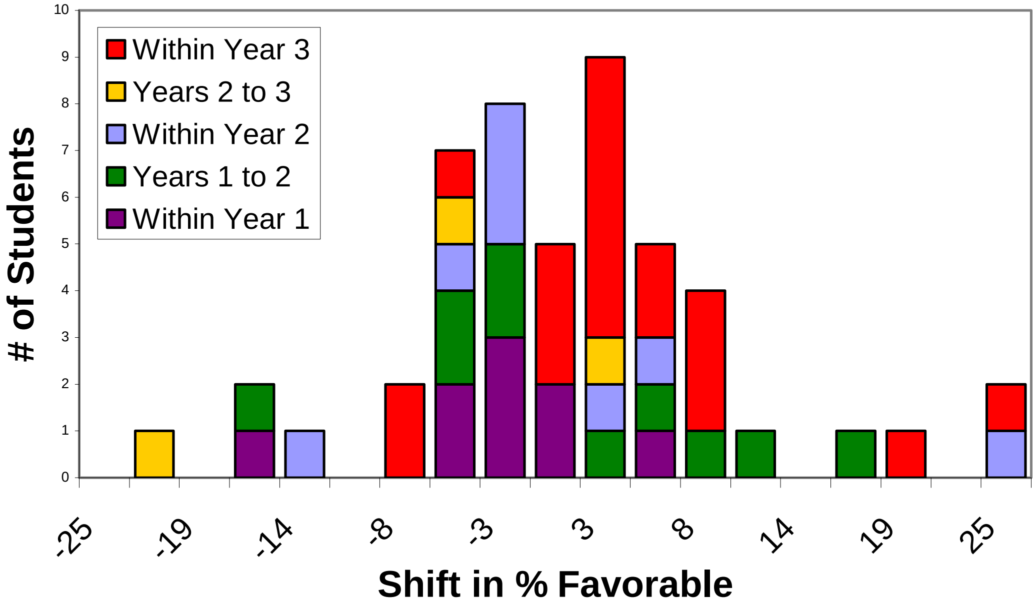


Figure 4-4: Histogram of the % shift in favorable score for multiply-surveyed students. Shift was calculated using first and second survey score.

Of the 148 physics majors surveyed, 51 responded to the survey more than once, generally within one or two quarters of their initial response. The longitudinal data on this subset of students allow changes in students' responses to be monitored over time. The average difference between the percentage of favorable responses on students' second and first surveys is -0.1%, with a standard error of the mean equal to 1.4%. A two-tailed, paired sample t-test shows no statistically significant difference between the percentage of favorable responses in students' first and second surveys, t(50)=0.075, p=0.941. A similar result was found among students in Year 3 only (students transitioning from 100A to 100C or 130A). Figure 4-4 shows a histogram of the percentage shift in the number of favorable responses for students who completed the survey multiple times during this study. The figure is color-coded to show students' shifts over within-year transitions and between-year transitions. The distribution of each of these transitions is closely centered on a 0% shift.

These longitudinal data indicate that for students in years 1-3, most individual respondants' overall responses to CLASS do not change over time. The cross-sectional and longitudinal data taken together suggest that physics majors begin the degree program with a relatively high degree of sophistication (compared to their non-physics major peers) that does not change during the first three years of the program. Furthermore, if the Year 1 students are divided into two groups – those who took the CLASS as a pre-test at the beginning of 4A and those who took CLASS for the first time as a post-test in either 4A or 4B - the averages of these two groups are 71% (standard error = 5%) and 73% (standard error = 4%), respectively, indicating that entering physics majors are just as expert-like as majors who have taken one or two university-level physics courses. These data suggest that the expert-like views assessed by CLASS are a preexisting characteristic of students who choose to be physics majors, rather than a characteristic that is learned or acquired during the degree program.

The transition from first year physics majors to physics grad/faculty experts does not seem to be smooth and continuous. Incoming physics majors are more expert-like than engineering students and physics majors are less sophicated than the experts used to calibrate CLASS. Students in Year 3 are less expert-like than students in Year 4, although both Year 3 and Year 4 are statistically comparable to both Years 1 and 2. These data are interpreted as students' views being stable over the first three years of study followed by a significant increase between Year 3 and Year 4. Majors in the fourth year of study have a comparable level of sophistication to the physics graduate students. This result is not necessarily expected, as graduate students are a special subset of students with diverse undergraduate backgrounds, self-selected by the desire to get a post-graduate degree and filtered by the admission standards of graduate programs.

Analysis of Specific Views

In addition to evaluating the students' overall sophistication, individual survey items and groups of items were examined in order to determine how specific views differ among the different years. The percentage of students in each year that responded favorably for each survey item is reported in Appendix III. Items #4, 7, 9, 31, 33, and 41 are not reported because there is no consensus expert response for these items, and in a standard CLASS analysis they are not scored. Figure 4-5 shows the favorable response rate for selected survey items.

The groups of items that were analyzed are those defined as CLASS categories. Researchers at the University of Colorado identified these categories by

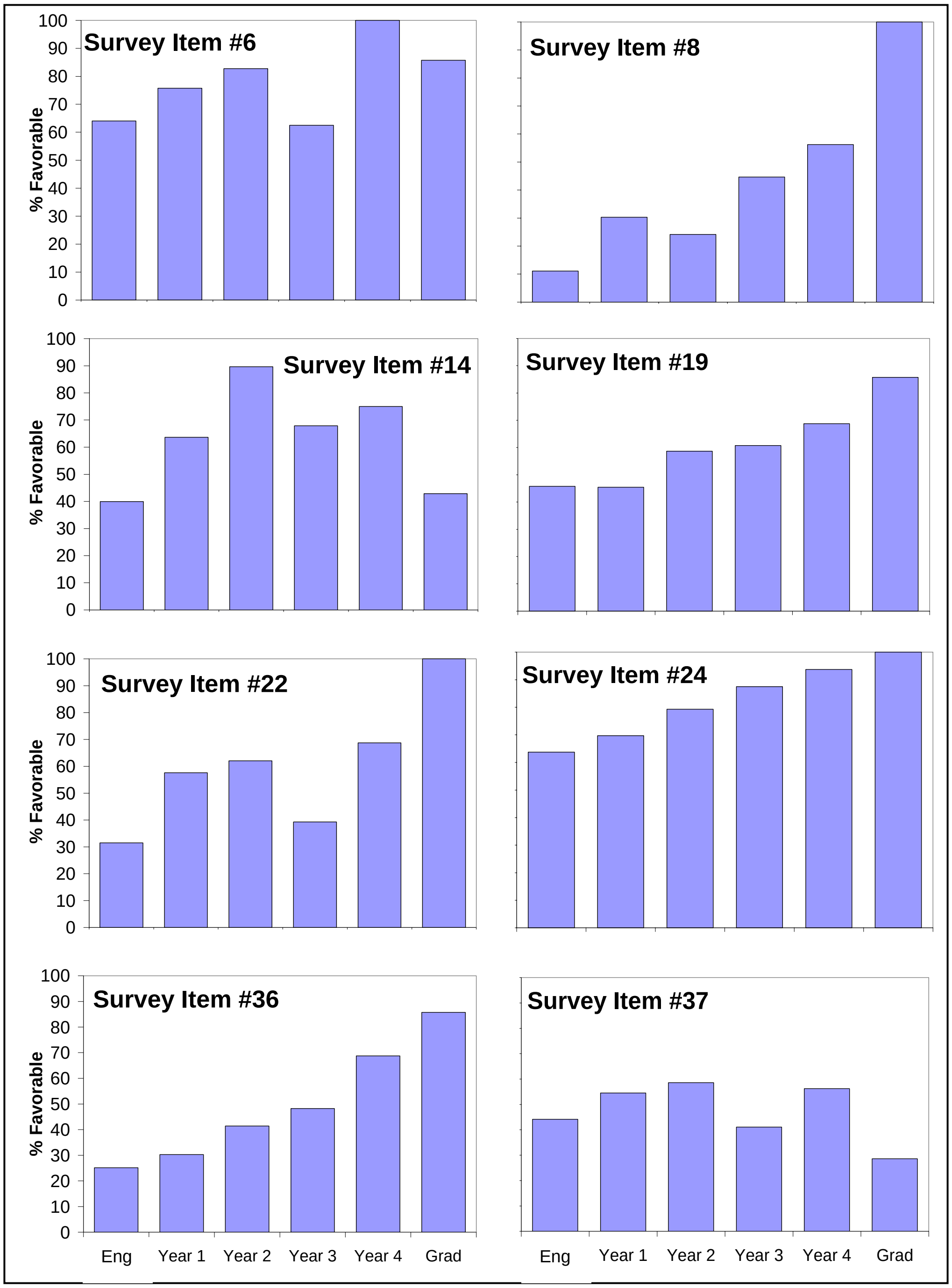


Figure 4-5: Distributions of favorable responses for selected survey items.

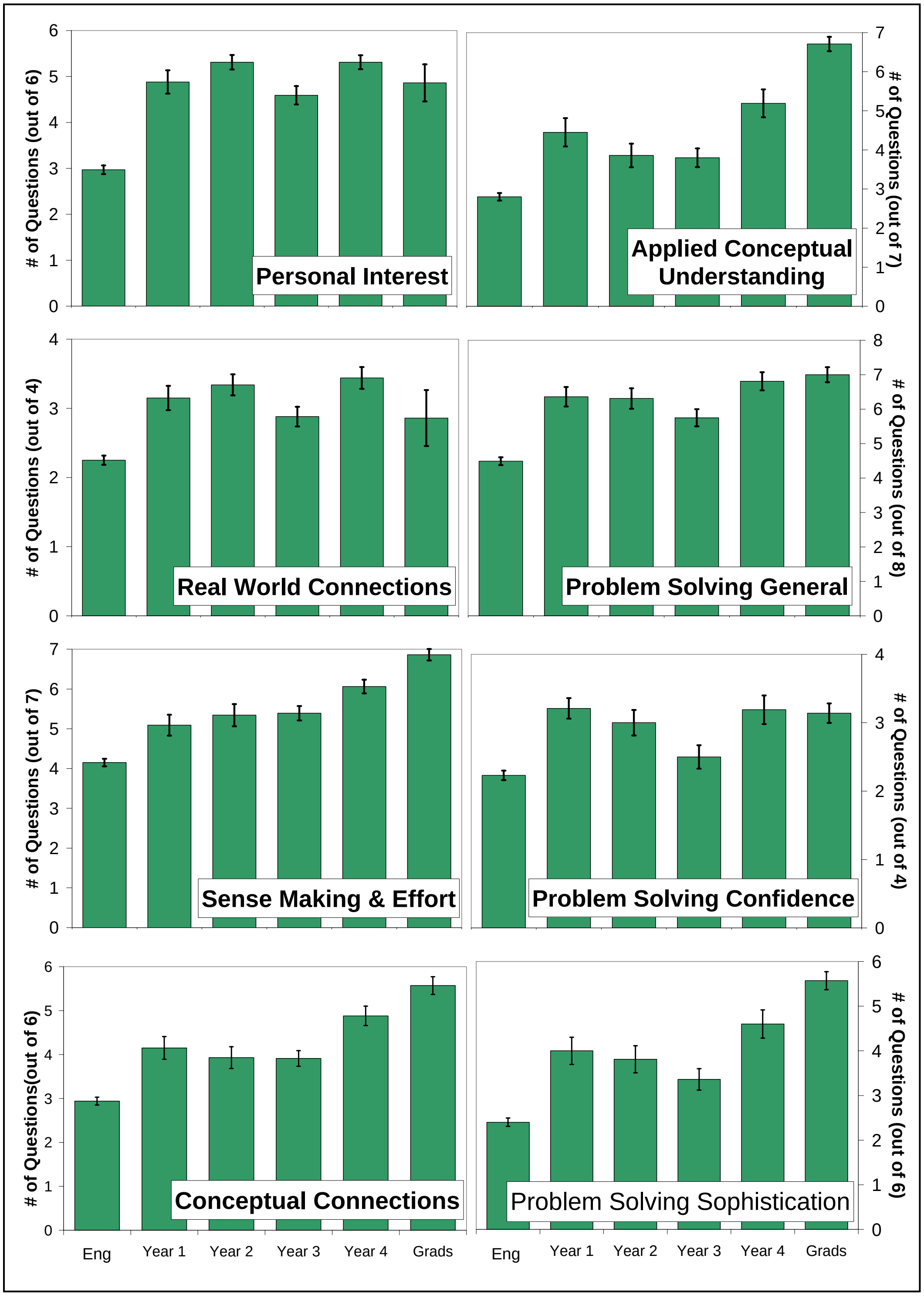


Figure 4-6: Bar charts of the average number of favorable responses for each of the 8 CLASS categories. Error bars indicate standard deviation of the mean.

looking for patterns in the responses of introductory physics students [13]. Figure 4-6 contains bar charts indicating the average number of favorable responses within each category for students in each year of study. Appendix II summarizes results from Games-Howell post-hoc tests of these data.

In nearly every category, the engineering students have a significantly lower rate of favorable responses compared to any of the physics majors. This result is consistent with engineering students being generally less expert-like than physics majors as measured by CLASS. This trend is particularly interesting in the Personal Interest (PI) category, where the personal interest score is uniform for physics majors and does not differ by year. The differences between the engineers and the physics majors are consistent with other reports that (unsurprisingly) physics majors have more personal interest in physics than engineering students [70]. These data suggest that the view of physics as relevant to the student's everyday life plays an important role in the selection of a physics major.

One category that has an unusual trend is the Real World Connections (RWC) category, where the graduate students have a decreased favorability compared to other physics majors. In this category, the responses of the graduate students and the engineering students are statistically similar. The more novice-like views of graduate students in this category – relative to their overall responses – may reflect the abstract nature of topics and problems typically addressed in graduate level courses. In fact, the only items for which fewer than half of the graduate students chose a favorable response were Item #14 ("I study physics to learn knowledge that will be useful in my life outside of school" – PI category) and Item #37 ("To understand physics, I sometimes think about my personal experiences and relate them to the topic being analyzed" – RWC category). It seems reasonable that graduate students, who take specialized, highly mathematical, abstract courses would experience a disconnect between their experiences doing physics and their everyday experiences.

In looking at the CLASS categories, a decrease in favorability at Year 3 compared to Year 4 is observed in every category, although this difference is statistically significant only for the Conceptual Connections (CC) and Applied Conceptual Understanding (ACU) categories. The two survey items that most dramatically share this trend are Item #6 ("Knowledge of physics consists of many disconnected topics" – CC and ACU categories) and Item #22 ("If I want to apply a method used for solving one physics problem to another problem, the problems must involve very similar situations" – ACU category). Note that these two items also show a difference between Years 2 and 3. Year 3 students indicated a increased sense of disconnection between physics topics and a decrease in recognizing a general applicability of problem solving methods. These results are interpreted by considering that the courses taken during Year 3 are the first upper division courses that undergraduate physics majors are required to take (Lagrangian Mechanics, Electrodynamics, Quantum Mechanics, etc.). In light of the courses taken and the data collected during the interviews (see the discussion of Lagrangian techniques in Chapter 6), these survey results may reflect the students' reactions to the use of more specialized techniques and to the increased mathematical difficulty of these courses compared to the students' lower division experiences.

The CLASS contains three categories specifically referring to problem solving views and practices – Problem Solving General (PSG), Problem Solving Confidence (PSC) and Problem Solving Sophistication (PSS). All of these categories show a difference between the physics majors and engineers. The physics-major years are similar to each other with a decrease at the Year 3 level, although the decrease in PSS category is not statistically significant. These data are interpretted to mean that physics majors begin undergraduate study with fairly expert-like views about problem solving (i.e. the role of mathematical equations and the effort required for solving problems). However, the Year 3 students show a slight decrease in sophistication.

A particularly interesting survey item related to problem solving is Item #8 ("When I solve a physics problem, I locate an equation that uses the variables given in the problem and plug in the values"). This item shows the largest range of responses within the physics major. The favorability rate of all undergraduate years is less than 60%, while all the Graduate students gave a favorable response. The unfavorable responses of Year 1 and 2 students are striking because it suggests that students in the first two years of undergraduate study find the plug-n-chug strategy to be productive in solving physics problems. The increase in favorable responses among Year 3 and 4 students may reflect the more complex nature of upper division coursework and assignments. Students' views of plug-n-chug techniques is discussed further in Chapter 7.

The jump between Year 4 and graduate students for Item #8 is particularly large, and may be due several possible contributing factors. This shift in behavior could be related to a shift in expectations – graduate students may expect to gain a deeper understanding of physics from doing problem sets, while undergraduates may view problem sets as exercises to practice using material covered in lecture. It could also be that the nature of physics problems that graduate students face is significantly different from those that undergraduates face, being less amenable to using a plug-n-chug strategy. A third possibility is related to the fact that most graduates have teaching experiences during their first year that most undergraduates do not. These experiences often involve evaluating the problem solving abilities of other students and identifying useful problem solving strategies. It seems reasonable that in identifying and explaining different strategies, TA's become more aware of the strategies they use in their own problem solving. Interviews are needed to determine if, and to what extent, these factors influence graduate students' views.

The Sense Making & Effort (SME) category shows a continuous increase of favorability by year. Items in this category that reinforce this steady progression are Item #24 ("In physics, it is important for me to make sense out of formulas before I can use them correctly") and #36 (There are times I solve a physics problem more than one way to help my understanding"). Both of these items address sense making in relation to problem solving, although interviews with students are needed to clarify if and how students see these items as being related. An item that is not included in this category (or any defined CLASS category) but also shows a steady progression of increased favorability within the physics major is Item #19 (“To understand physics I discuss it with friends and other students”). Again, this item seems to be related to sense making activities. It appears that students’ ideas about what activities are helpful for making sense out of physics ideas becomes steadily more expert-like during undergraduate study.

Polarization of Responses

A typical analysis of CLASS data treats responses as if they are on a three-point scale (favorable, unfavorable, and neutral), which is the standard way of binning responses in analyses of Likert scale surveys [71]. The response choices are treated as ordinal data, that is, the choices are categorical and ordered, but the differences between choices are not interpretable and may be different for different individuals. For example, two students may have the same strength of belief that “nearly everyone is capable of understanding physics if they work at it”, but one student may be more inclined to choose strongly agree and the other student (weakly) agree because there is no clear metric for indicating the strengths of their view. An advantage of this treatment is that the bins are larger, and although the precision in categorizing a student’s response becomes coarser, our confidence in accurately categorizing the favorability of the response increases.

Another way to treat the data is to preserve the ordering of the responses more strictly. Students who report that they strongly agree with a survey item are assumed to have stronger views than students who (weakly) agree. The data are then binned by reported strength of view, as opposed to favorability. Strongly agree and strongly disagree are binned together, as are (weakly) agree and (weakly) disagree. Figure 4-7 illustrates the different binning strategies that have been described. An analysis was performed using the "polarization" binning to gain insight into how strong, or how polarized, the students report their views to be.

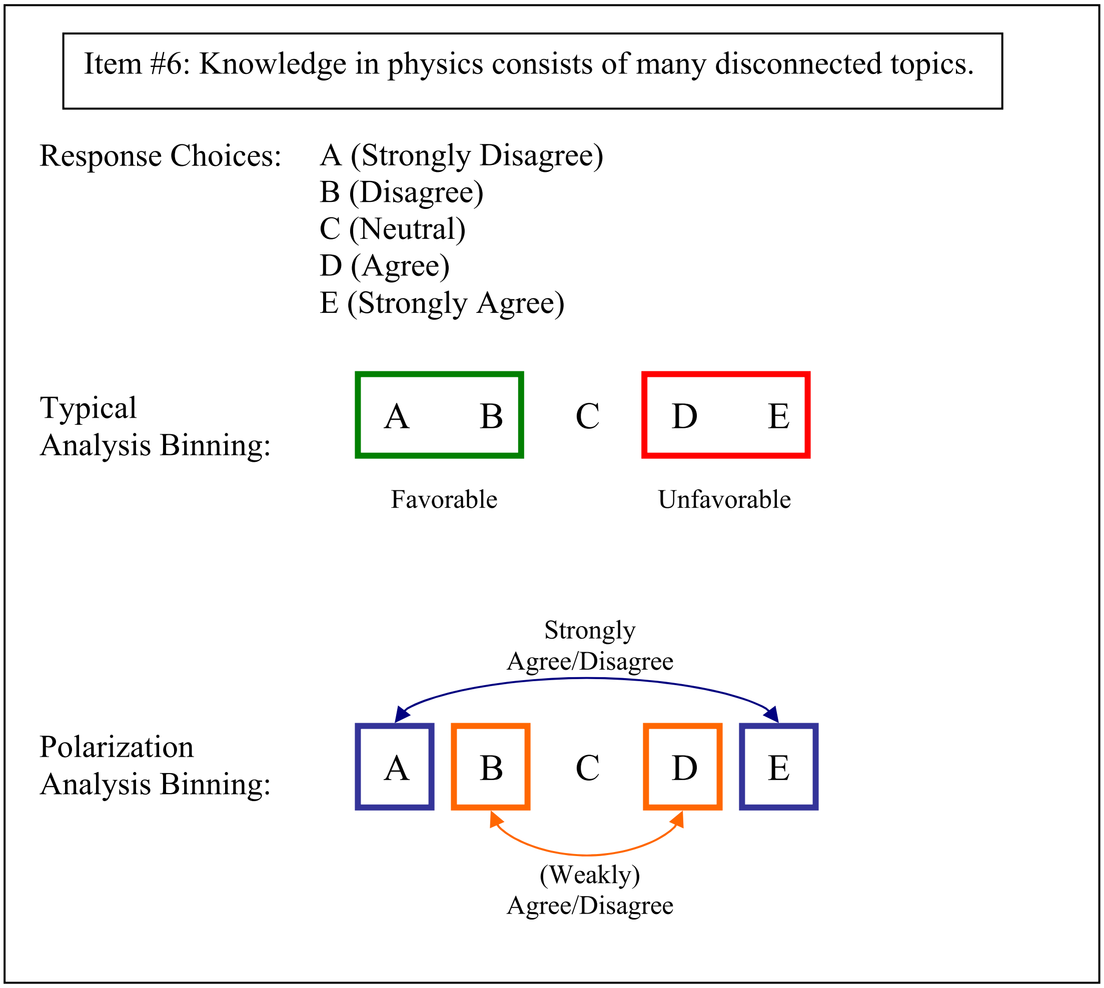


Figure 4-7: Diagram illustrating how response choices are binned in a typical analysis of CLASS data and a polarization analysis.

Figure 4-8 shows the average percentage of responses for each year of study. The figure indicates that students in every year chose a (weakly) agree/disagree response more often than an extreme or neutral response (though this difference is statistically significant only for the engineering students and Years 1-3). Engineering students chose an extreme answer less often than the physics majors, while the graduate students chose a neutral response less often than the undergraduate physics majors and the engineering students. Furthermore, within the majors, the general trend from Year 1 to Grads is towards more strong responses and fewer neutral responses. However, in general these differences are not statistically significant at the $p < 0.05$ level by Games-Howell post-hoc testing.

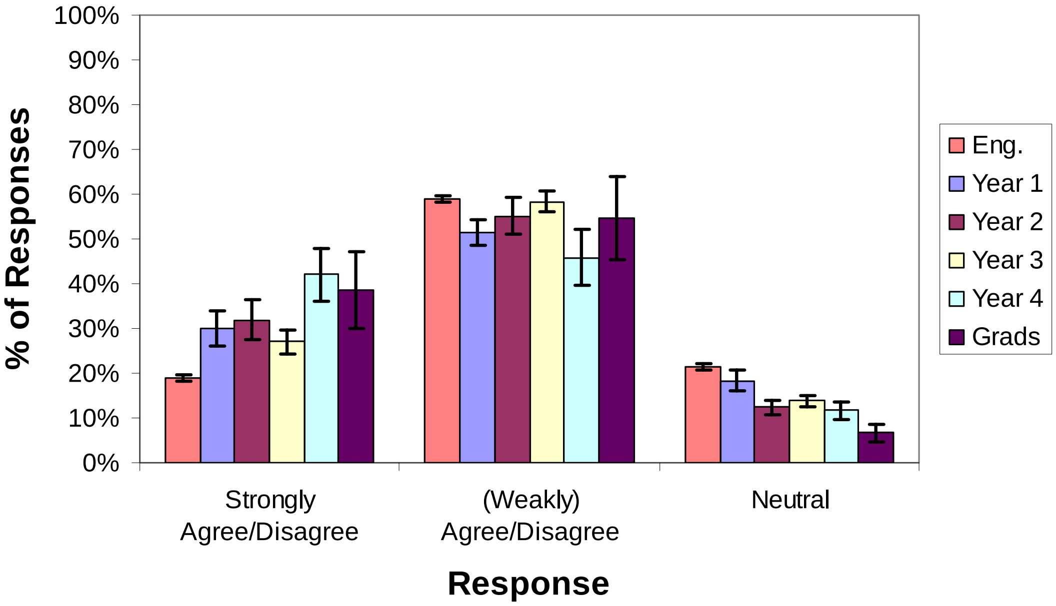


Figure 4-8: Responses on five-point scale for each year averaged over all survey items. Errors bars represent the standard error of the mean.

Figure 4-9 shows the average percentage of answers that are extreme (strongly agree/disagree) for each year of study. These data are the same as the Strongly Agree/Disagree column in Figure 4-8, but now information about the favorability of the responses is included. Figure 4-8 and Figure 4-9 indicate that engineers chose an extreme answer less often than any of the groups of physics majors, but Figure 9 shows that a sizable portion of these extreme responses were unfavorable responses. In contrast, the fraction of unfavorable extreme responses is smaller for all of the physics major groups. None of the extreme responses given by the graduate students was unfavorable.

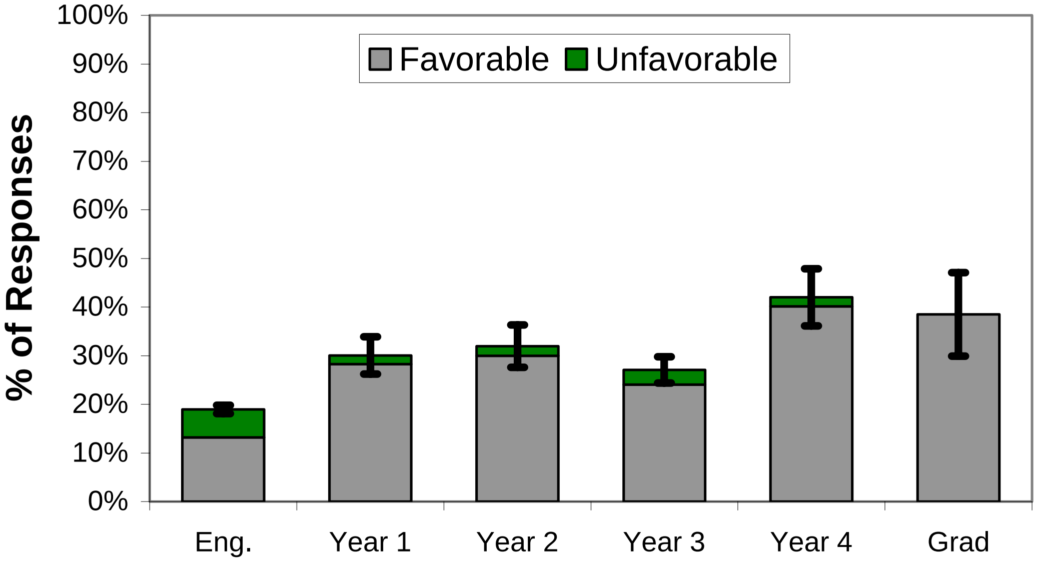


Figure 4-9: Percentage of responses that were either strongly agree or strongly disagree by year. Error bars indicate the standard error of the mean. The fractions of these extreme responses that are favorable and unfavorable are indicated by color.

These results suggest that students with more experience in the physics major have more polarized views. Not only are more experienced physics students more expert-like, but they generally report their views in stronger terms, more often responding strongly and less often responding neutral than engineering students. This is consistent with students' views becoming more codified as they finish their undergraduate study and enter graduate school. However, these conclusions represent trends rather than statistically significant results, and that this analysis requires an assumption about the ordering of the responses that may not be strictly valid between students.

Discussion

The cross-sectional and longitudinal CLASS data show that physics majors' overall views do not change significantly during the first three years of undergraduate study, to the extent that these views are measured by the survey. In light of the similarity of sophistication among entering physics majors and students in the first three years of study, view-based selection of physics majors probably occurs when students are entering the physics program. These results are consistent with Seymour & Hewitt's inability to link students' decisions to leave science and engineering majors with any specific views or behaviors beyond the development of coping attitudes and strategies [72]. Our results are probably conservative measurements of view-based selection as the students involved in this study have chosen to participate in introductory physics courses designed specifically for physics majors. These students are likely to have a strong commitment to the program, and may be more resilient to selection pressures than students who “try out” the major in a more general introductory program.

Students’ survey responses show that physics majors enter the university with relatively expert-like views about physics compared to their peers in the engineering majors. This trend is evident in the overall survey score, in the individual survey items, and in categories of items. This result is somewhat unexpected considering that engineering students and physics majors often have very similar academic experiences with science, and that most physics majors and engineering students take physics prior to entering the university.

Why is it, then, that incoming physics majors have more expert-like views about physics than engineering students? There are several possible explanations. First, students who have enough interest in physics to declare a physics major may be more likely to have extracurricular experiences with physics (ie. popular science media, science museums, after-school clubs, etc.), where expert-like views could be developed. Another possibility is that this result reflects a cultural influence. Students who grow up in families and/or communities whose epistemological values are aligned with those of the physics community may be more likely to choose a physics major.

The fourth year of undergraduate study seems to be an epistemological transition period between the early undergraduate years and grad school. It is unlikely that the difference between Year 3 and Year 4 is due to attrition of less expert-like students because few students leave the major so far along in the program. For instance, of the 70 physics majors enrolled in junior level physics courses in Fall 2004, only 6 students left the physics major during the 2004-2005 academic year while 5 students transferred into the program from other majors. Instead, the difference in the Year 3 and Year 4 data may be due to students at this stage assuming views they know to be accepted by the community of practicing physicists. This suggestion is made in light of the finding that introductory students study can accurately identify expert-like survey responses [70]. Year 4 students are finishing their undergraduate program and deciding if and where they are going to apply for graduate school. This process involves deciding whether they want to pursue a career in physics as well as convincing recommenders and admission committees that they are desirable candidates. Additionally, many senior level undergraduates begin to participate in research projects. Of the 49 physics majors who graduated in Spring 2006, 11 had participated in research projects for course credit with UCSD physics department faculty. Interviews with physics majors revealed that some upper level students begin to identify themselves as being physicists. This suggests a connection between students' identities as physicists and reporting beliefs that are consistent with that identity.

Our data raise questions about whether the defined CLASS categories are appropriate for studying physics majors. The CLASS categories were defined by looking at patterns of students' responses so that the grouped items are connected from the students' perspectives, rather than grouping items that are connected from the researchers' perspective [13]. This analysis relied on responses of students in introductory physics courses, most of whom were not physics majors. Upper division physics majors have more experiences with physics to draw from in responding to the survey items, and it is possible that they interpret some of the items differently than introductory students. Therefore, the categories defined for introductory students may not be entirely appropriate for more experienced physics majors. However, there is not enough data to perform a meaningful factor analysis to define categories specific to physics majors. Furthermore, the variability of responses is smaller among upper division students, making identifying categories with a factor analysis more difficult.

Another way to group survey items is to look at the progression of responses across the major. In looking at individual survey items, different patterns of progression emerge. For example, some items, like Item #36, have an increasing rate of favorable responses between Year 1 and the Grads. Others, like Item #37, have a decreased response rate for the Grads. Although, again, there is not enough data points to do a meaningful statistical analysis of these patterns, defining developmental subsets of items in this way will provide more insight into how students develop into physicists.

Of course, this study suggests new questions. What are the implications for how physics majors are educated? What happens to the development of physics majors if expert-like views are taught explicitly? Is there a limited pool of potential physics majors, consisting of students who meet high attitudinal standards? Can physics departments recruit students whose views predispose them away from the physics major? How could this be accomplished? Is it possible to design an undergraduate physics program where students with other views are more willing to participate?

Additionally, although UCSD has a fairly traditional physics degree program, physics programs vary across institutions, and it is expected that different trends may be seen across different physics departments. Multi-institutional comparative studies would address questions about the effects of different physics degree programs on the development of students' views.

Conclusion

Physics majors come to the university with views about physics that are relatively expert-like. Overall, these views are consistent throughout most of the undergraduate program, with an increase for students in the final year of study. Graduate students have more expert-like views than undergraduates, and physics majors have more expert-like views than engineering students enrolled in introductory physics courses. These results suggest that physics majors' overall attitudinal sophistication, as measured by CLASS, is a preexisting trait rather than something learned at the university. Upper-level physics majors tend to report their views in stronger terms.

The different views measured by CLASS appear to have different patterns of development. Views having to do with solving physics problems tend to be fairly expert-like. Physics majors at all levels report a strong personal interest in physics. Graduate students indicate a lack of connection between physics and their everyday experiences. Views having to do with sense making activities progressively become more expert-like across the physics major.

Physics majors' attitudinal sophistication does not change significantly at the undergraduate level. Furthermore, survey results provide little evidence to support a claim that students leave the major for reasons related to their views. However, a student's views may play a role in the decision to enter an undergraduate physics degree program.

Acknowledgements

Chapter 4, in part, is a reprint of the material as it appears in the Physics Education Research Conference Proceedings 2006, Gire, Elizabeth; Price, Edward; Jones, Barbara, AIP Press, 2006.

Chapter 5: Selection of Interview Participants

This chapter will outline how interview subjects were selected. First, the criteria used to identify potential interview subjects will be described, followed by a discussion about students' course grades and CLASS score. The chapter will end with an overview of the final interview data set, including a summary of the students' experiences studying and teaching physics.

Selection Criteria

A purposive selection [73] of physics majors was made, targeting students who represented a range of degree progress, CLASS Score and course grades. These factors were chosen so that the students' who were interviewed would represent a range of views and abilities, and students were selected as to maximize the variation of these factors. The interview data set was meant to give a sense of typical physics majors, though the it is too small to be statistically representative. In order to identify potential interview participants, the physics course enrollments for Winter 2006 were matched against the CLASS data set (excluding Winter 2006 data, which had not been taken yet), and students who had previously taken the survey were identified. For each of these students, several pieces of information were collected: the course in which the previous survey score had been taken, the student's final grade for that previous course, the average survey score (and standard deviation) for that previous course, and the average course grade (and standard deviation) for that previous course. Averages and standard deviations were found using data from students of all majors, not just physics majors. For many courses, only final letter grades were available, and letter grades were available for all courses prior to Winter 2006. For consistency, all letter grades were translated into numerical grades based on UCSD's convention of assigning grade points (See Table 5-1).

Table 5-1: Rubric for converting letter grades to numerical grades

Letter Grade	Numerical Grade
A+	4.3
A	4.0
A-	3.7
B+	3.3
B	3.0
B-	2.7
C+	2.3
C	2.0
C-	1.7
D	1
F	0

Because of substantial variation in course grade distributions, the students' course grades were then normalized by taking the difference between each student's grade and the average grade assigned in the course, and then dividing by the standard deviation of course grades. The survey scores were similarly normalized.

$$\text{Normalized Course Grade} = \frac{\text{(Student's Course Grade)} - \text{(Average Grade in Course)}}{\text{(Standard Deviation of Course Grades)}}$$

Normalized Course Grade indicates where in the distribution of grades the individual student's grade falls, measured in number of standard deviations. A negative Normalized Course Grade indicates that the student's grade is less than the average grade given in the course. Letter grades were not available for the Winter 2006 Physics 4A course because the term had not yet completed, so the students' first quiz scores were used as a proxy for course grade. In this case, the students' numerical

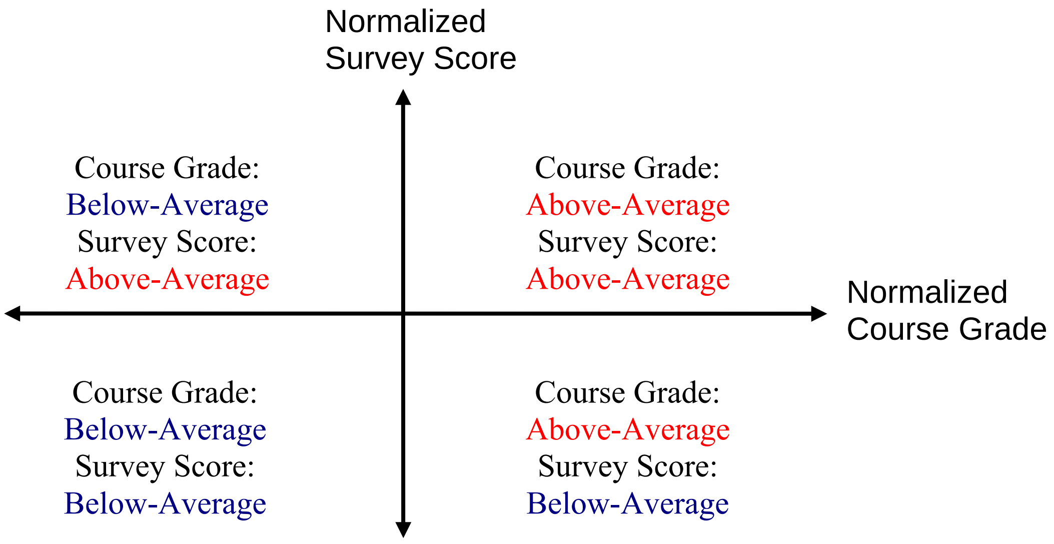
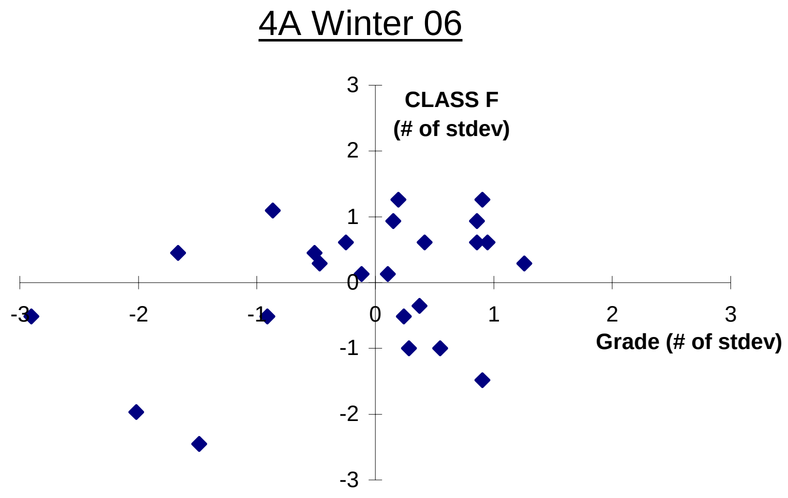


Figure 5-1: Illustration of quadrants for graphs of Normalized Course Grade and Normalized Survey Score



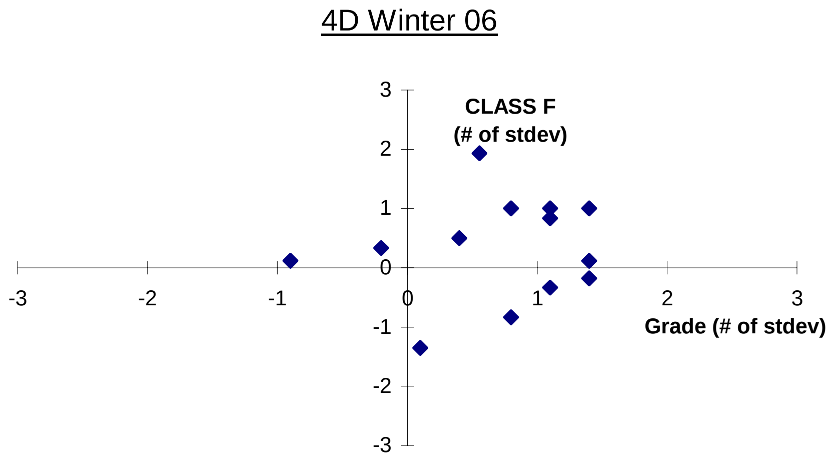
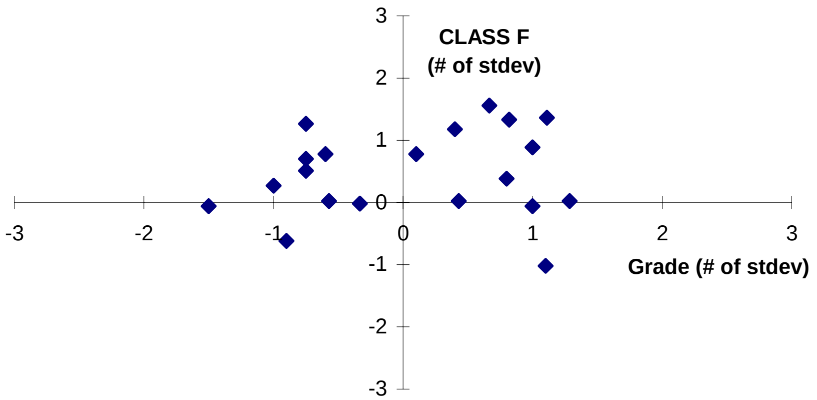


Figure 5-2: Graphs of Normalized Course Grade vs. Normalized CLASS Score for students enrolled in physics courses during Winter 2006 (4A, 4D, 100B, 130C). The data are based on survey scores and grades from previous courses. Each data point represents student data from the course taken most immediately prior to Winter 2006 in which the student was surveyed.

100B Winter 06



130C Winter 06

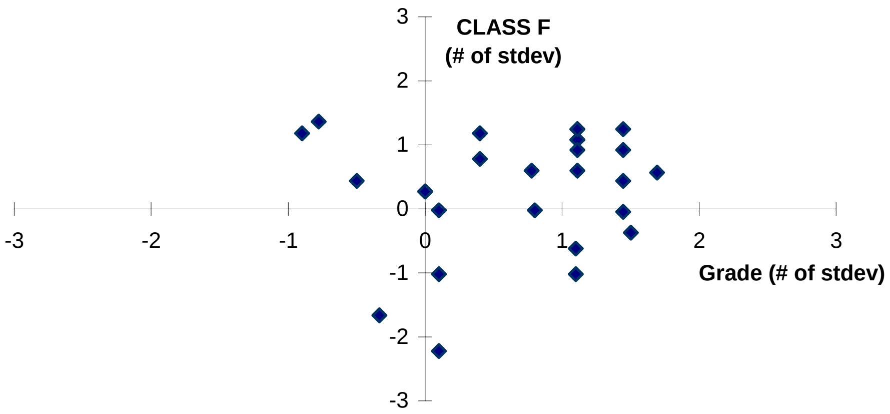


Figure 5-3: Graphs of Normalized Course Grade vs. Normalized CLASS Score for students enrolled in physics courses during Winter 2006 (4A, 4D, 100B, 130C), Continued.

grades were available and were used for normalization. Normalized course grade and survey score were plotted against each other for each of the Winter 2006 courses, and four quadrants were identified:

Several students from each quadrant were invited to participate in the interviews from each of the four experience levels. Although many students were invited, only a few elected to participate. One graduate student was invited to participate in a practice interview using the final protocol. The discussion during this interview turned out to be interesting and valuable, and given the limited number of interview participants, it was included in the final interview data set. The protocol for these students differed from the final protocol in that the problems were presented in a written format and included numerical quantities, and this student was not asked to comment on sample solutions.

Correlation of Course Grade and Survey Score

Implicit in the criteria used to select interview participants is that students' course grades are not correlated with their CLASS scores. In light of research that links attitudes and beliefs with conceptual learning [34, 41], this lack of correlation is not necessarily expected. However, the plots of Normalized Course Grade vs. Normalized Survey Score (Figure 5-2) are populated in each of the four quadrants, suggesting a lack of correlation between these two quantities. Below is a plot of Numerical Course Grade and Survey Score for all of the undergraduate physics majors who were surveyed prior to Spring 2006 (n = 145). These data include students who were surveyed multiple times, with each data point consisting of a survey score-course grade pair. The data does not include the 4A pre-test taken in Winter 2006.

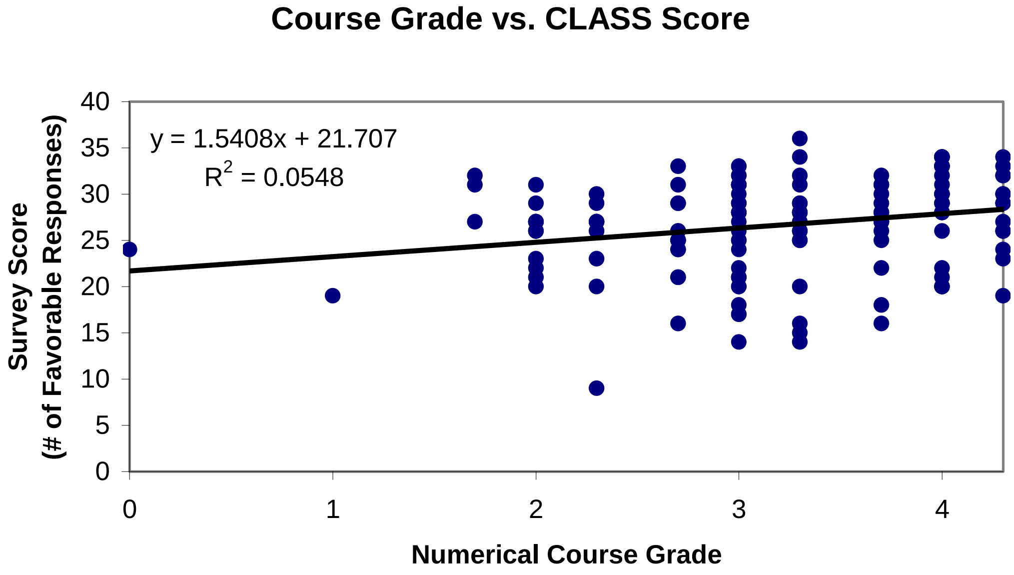


Figure 5-4: Plot of Numerical Course Grade vs. Survey Score for all physics majors surveyed prior to Spring 2006.

Although the best fit line has a slight positive slope, the correlation coefficient R^2 = 0.05 indicates that there is in fact no correlation between numerical course grade and overall survey score. Normalized Course Grade and Normalized CLASS Score have a similarly low correlation coefficient. Furthermore, course grade does not correlate with the subset of survey items that are included in the CLASS Problem Solving Categories (survey items #5, 13, 15, 16, 21, 22, 25, 34, 40, and 42).

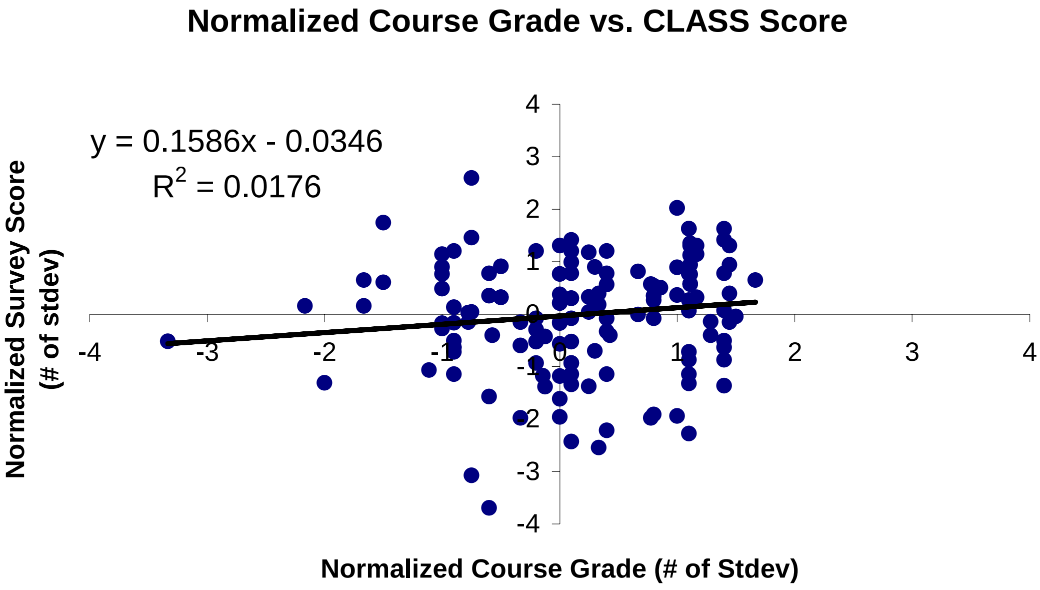


Figure 5-5: Plot of Normalized Course Grade vs. Normalized Survey Score for all physics majors surveyed prior to Spring 2006.

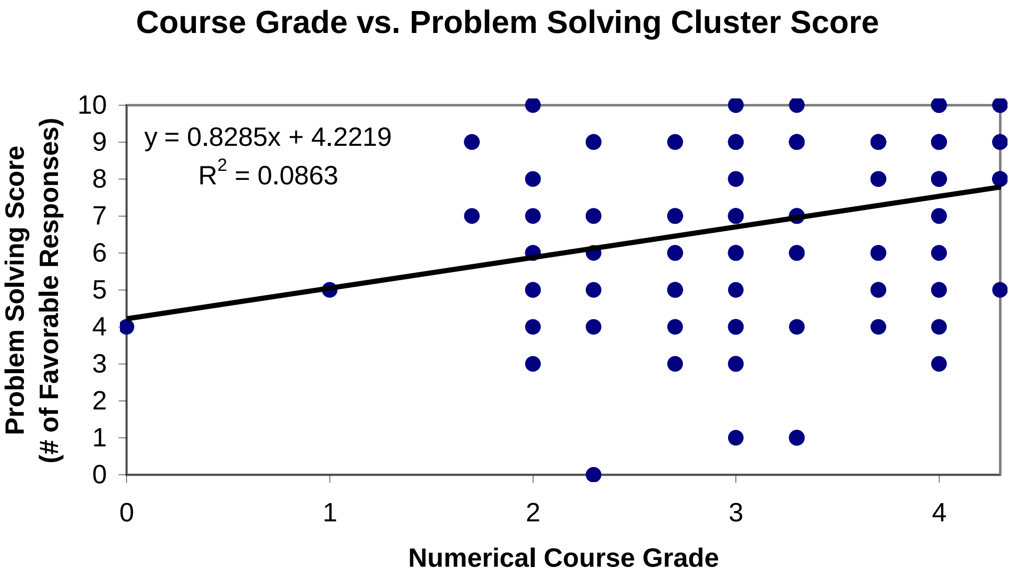


Figure 5-6: Numerical Course Grade vs. Problem Solving Score for all physics majors surveyed prior to Spring 2006.

Therefore, both CLASS score and items included in the CLASS Problem Solving Categories are found to be uncorrelated with course grade. CLASS scores and course grades are independent measures of students' abilities and characteristics, and both were considered when inviting students to be interviewed. It is expected that the interviewed students will display a range of problem solving abilities and views.

A lack of correlation between survey score and course grades is consistent with research that shows some students' study habits do not necessarily reflect their personal epistemologies and are influenced by course pace and the students' course expectations [37, 38]. Students tend to study in ways that they think will maximize their grades, which may conflict with what they think will help them attain deep conceptual understanding [35, 37].

Summary of Final Interview Data Set

Table 5-2: Students included in final interview data set. Names are pseudonyms.

Interview Participant (pseudonym)	Year of Study (at time of interview)
Zoe	First
Simon	First
Jenny	First
Kaylee	Third
Hoban	Third
Malcolm	Fourth
Nathan	Grad (fourth year)

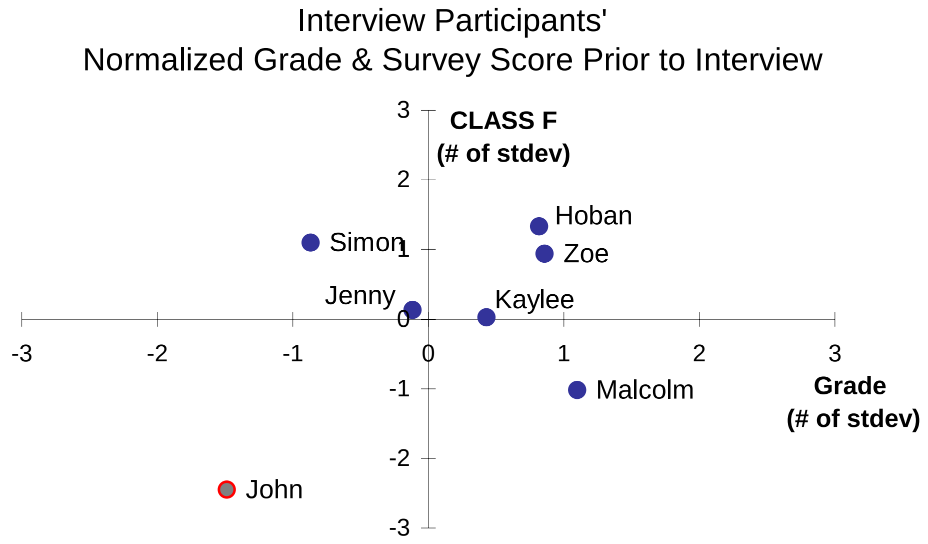


Figure 5-7: Plot of Normalized Course Grade and Normalized CLASS Score for interview participants. Names are pseudonyms.

As shown in Figure 5-7, the interview participants occupy all of the quadrants of the normalized course grade and survey score plot, except for the lower left (below average course grade and survey score). John was a freshman who dropped out of his freshman physics course and switched majors just before he was interviewed. During the interview, he was unable to solve any of the physics problems posed. Due to his lack of physics knowledge, his interview does not address the research questions related to problem solving and was excluded from the final data set.

In inviting several students from each experience level, it was hoped that there would be enough students to compare across experience levels. However, only seven interviews are included in the final data set. Therefore, these interviews will be considered together as a single group representing physics majors as an intermediate experience level between novices (non-majors in introductory physics) and experts (physics faculty).

Table 5-3: History of CLASS Score for interview participants

Interview Participant Pseudonym	**Previous CLASS Score**			**CLASS Score at Interview**	
	Course, Quarter	# **Favorable** Responses	# **Neutral** Responses	# **Favorable** Responses	# **Neutral** Responses
John	*4A, Winter 2006 (Pre)*	*9*	*21*	*18*	*8*
Zoe	4A, Winter 2006 (Pre)	30	1	-	-
Simon	4A, Winter 2006 (Pre)	31	2	24	7
Jenny	4A, Winter 2006 (Pre)	25	4	27	7
Kaylee	4E, Spring 2005	25	8	25	5
Hoban	2C, Winter 2005	28	1	28	1
Malcolm	100A, Fall 2004	20	8	31	1
Nathan	-	-	-	31	1

Most students were surveyed at least twice: once before the interview ("Previous CLASS Score") and once during the interview, although Zoe was only surveyed before the interview and Nathan was only surveyed during the interview. There is some fluctuation between the students' previous responses and their interview responses. Malcolm's scores show the most dramatic fluctuation. His previous survey score was taken during his 3rd year of study and he was interviewed during his 4th year of study. Some of the students indicated that they took the survey more seriously during the interview than they had previously. The interview survey scores generally follow the trends discussed in Chapter 4.

During the beginning of each interview, the students were asked to discuss their physics backgrounds. They talked about their histories studying physics, their teaching experiences and their plans after finishing their undergraduate degrees. This information is presented in the two tables below. The first table includes only freshmen; the second table includes the more experienced students.

All of the interview participants are physics majors. Most of the undergraduates are thinking about pursuing graduate studies in physics. Two of the interview participants have formal teaching experience (Malcolm and Nathan). All of the undergraduate students were enrolled in physics courses at the time of the interview. Only one of the undergraduates (Hoban) had transferred from a community college, and this same student was the only interview participant who had not studied physics in high school. Three of the seven interview participants were female, resulting in an over-representation of women in the final data set.

Table 5-4: Background of freshman interview participants

Interview Question	Zoe	Simon	Jenny
How many years has the student been studying at UCSD?	1st Year	1st Year	1st Year
Is the student a physics major?	Yes	Yes	Yes, thinking about an astrophysics specialization
Did the student study physics in high school?	Yes	Yes	Yes
What physics courses is the student currently taking?	4A	4A	4A
Is the student male or female?	Female	Male	Female
Does the student have any teaching experience? (How much?)	No	No	No
2-series or 4-series path?	4-series	4-series	4-series
What's she/he going to do after graduation	Maybe grad school	Maybe grad school	Maybe grad school

Table 5-5: Background of upper-division interview participants

Interview Question	Hoban	Kaylee	Malcolm	Nathan
How many years has the student been studying at UCSD?	1 year (3rd Year student, transfer in Winter 2005)	3rd Year	4th Year	4th Year Grad Student
Is the student a physics major?	Yes, astrophysics specialization	Yes, double major with Spanish Literature	Yes	Yes, physics & math double major
Did the student study physics in high school?	No	Yes	Yes – 11th and 12th grade in Montenegro	Yes
What physics courses is the student currently taking?	161, 110B, 100B	100B, 110B	130C, 100B, 140B	None
Is the student male or female?	Male	Female	Male	Male
Does the student have any teaching experience? (How much?)	No	HS Tutoring	TA'd several under-graduate labs	TA'd several under-graduate labs
2-series or 4-series path?	Transfer Student	4-series, Introductory E&M and Lagrangian mechanics abroad	4-series	Under-graduate work at University of Cincinatti.
What's she/he going to do after graduation?	Air Force	Maybe grad school	Grad School	Post-doctoral position

Chapter 6: Characterization of Students' Problem Solving Approaches

In this chapter, the problem solving expertise of physics majors is characterized by examining their solution approaches of two classical mechanics problems. The analysis focuses on the types of solutions attempted, suggested, completed and preferred by the interview participants.

Methods

This section describes the detailed structure of the problem solving portion of the interviews and the methods used for analyzing problem solving episodes. The "Interviews" subsection of the "Methods" chapter includes a more general discussion of the interviews and how they were conducted.

The students were asked to solve two classical mechanics problems. The area of classical mechanics was chosen because it is the topic covered in the first introductory physics course for physics majors and is therefore familiar to all of the students that were interviewed. At the time of the interviews, two of the freshmen (Zoe and Jenny) had nearly completed this course, and Simon had just completed it. All of the other students had completed an introductory course in classical mechanics.

The problems were presented to the students verbally, and the students were provided with blank paper, a pen or pencil, a calculator, and a summary of classical mechanics from a preparation book for the Graduate Record Examination (GRE) Physics subject test. Typically in a physics course, students solve problems that are posed in a text format and the students are expected to generate written solutions. During the interviews, it was hoped that the students would be as detailed as possible in discussing their problem solving processes, including aspects that may remain unexpressed in a more typical setting. The questions were presented verbally in order to encourage students to discuss their reasoning aloud.

It was anticipated that the interview participants may feel a certain amount of pressure during the problem solving portion of the interviews, similar to what they might feel in an oral exam situation. Oral exams are very rarely given in this department and, as a general rule, physics majors are only asked to solve problems for homework problem sets or exams. For homework problem sets, students generate written solutions outside of class. For exams, solutions are written either in class or at home, in the case of take-home exams. Students are rarely asked to solve problems in front of others or asked to explain their solutions. To alleviate anxiety that may be caused by the unusual circumstance of the interview, students were given a choice to either talk aloud while solving the problems or solve the problems quietly and then discuss their solutions. The first problem the students were asked to consider was an easy problem and was chosen to boost the students' confidence.

The first problem is a standard ball drop problem. The students were asked to consider a situation where a ball with a known mass is dropped from a known height. The students were then asked to find the speed of the ball just before it hits the ground.

This problem was chosen because it can be solved using a variety of approaches that are typically covered in introductory physics courses: kinematics, energy conservation, work, etc. The problem can also be solved using Lagrangian techniques that are taught in upper division courses – though this might be considered an excessively sophisticated approach for such a simple problem. It is a standard problem that nearly all physics students have solved using kinematics and energy conservation approaches.

For the ball drop problem, the students were initially asked simply to find a solution; no specific approaches were suggested to them. When they found a solution, the students were asked follow-up questions about their reasoning during that first solution. Then they were asked if they could think of other ways to solve the same problem. If they could, they were asked to solve the problem again using this new approach. If they could not think of one, a new approach was suggested by the interviewer. The students were asked to comment on each new approach that was attempted or suggested. The solution paths that were suggested to the students were done so with attention to the students' degree progress (i.e. freshman level students were not asked to try a Lagrangian approach).

The second problem was a more complex mechanics problem. The students were asked to consider the situation where Tarzan is swinging on a vine that can withstand a maximum amount of force before it would break. The students were then asked to find the maximum height from which Tarzan could swing from without the vine breaking. This problem was chosen because it is a challenging, multi-step problem. It can be solved using ideas and techniques that are standard in introductory physics courses, but unlike the ball drop problem, it is problem that most students have not solved before. This problem proved to be conceptually very difficult for many students. Several students in the first interviews questioned the premise of the problem, so the students in the later interviews were asked a variation of the same question: does the height that Tarzan starts swinging from matter? Is there a maximum height that he can start from before the vine will break?

The interviews were analyzed by making repeated passes through recordings and transcripts using a process of iterative coding. The intent of this approach was to develop concepts that explain observed behaviors by looking for patterns in the interview data. This is a generative type of analysis that complements the exploratory nature of these interviews particularly well. The first pass through the data was an open coding with broad codes identifying many types of behaviors and incidents that occurred during the interviews. Coding became more refined as the analysis became more focused on specific concepts. The coding schemes were generated while analyzing the interview data. Early codes were observational in nature; later codes were more abstract and interpretive.

A description of each student's problem solving trajectories was generated from transcripts, video and written work. Then, an analysis – using the framework described below – was done on comments made by the students about their solutions. Students' comments focused on several issues, for example, many students expressed a preference for a particular approach to the ball drop problem, and all students were asked to discuss the advantages and disadvantages of energy and kinematics approaches. Upper division and graduate students were asked if they could use a Lagrangian approach, and many students made comments about their comfort with this approach and the appropriateness of using this approach for these problems.

Based on expert/novice differences that have been identified in previous research, and discussed in Chapter 2, a framework was developed for analyzing students' solutions of both problems. This framework was used to characterize the problem solving expertise demonstrated by the students during the interviews. The students' written solutions to the interview problems are included in Appendix VI.

Table 6-1: Descriptions of Expert-like and Novice-like activities for different aspects of problem solving that occurred during the interviews.

Aspect of Problem Solving	Novice-like	Expert-like
Initial Solution Attempt	Starts with means-ends techniques using physics constructs that are closely related to the surface structure of the problem.	Starts with more general physics constructs (i.e. conservation principles).
Number of Solutions Suggested	Is only able to use one solution approach. Does not check solution by using multiple approaches.	Is able to suggest and use several solution methods. Is able to check solution by using multiple approaches that are experience-level appropriate (i.e. more experienced students should be able to discuss Lagrangian techniques).
Solution Preference	Prefers solutions involving constructs that are closely related to surface structure.	Prefers solutions utilizing fundamental physics constructs that are applicable in a variety of contexts.

These specific problem solving aspects were characterized as expert-like or novice-like for each student. The terms expert-like and novice-like are used to indicate the similarities of the interview participants' actions with the actions of expert and novice problem solvers that have been observed.

Previous research has found that novice problem solvers tend to use means-ends heuristics and focus on surface features of physics problem. In contrast, experts use more forward-thinking, concept-based approaches. Therefore, in the present work, initial solution attempts that use quantities closely linked with surface features (observable/perceivable quantities) were characterized as novice-like. Initial solution attempts that are based on more abstract physical quantities were characterized as expert-like. For these problems, kinematics and force approaches were characterized as novice-like, while energy approaches were characterized as expert-like. These characterizations were chosen in light on Singh's [57] observation that expert problem solvers tend to begin analyzing difficult problems by looking for conserved quantities, and Chi et al.'s [53] finding that experts are more likely to categorize problems based on major physical principles governing the solution of each problem (i.e. Conservation of Energy, Newton's Laws, etc). The characterizations of solution preference are similarly made.

Experts have been observed to check their answers using multiple approaches [60], while novices focus on one solution approach and rarely use different approaches to check answers on their own. Therefore, the number of solutions suggested is expert-like if the student suggests multiple approaches involving distinct physics constructs. The number of solutions is novice-like if the student only suggests one solution approach. On this issue, the difference in difficulty between the two problems is important. The Ball Drop Problem is an easy problem and it is assumed that the interview participants have solved it before using a variety of solution paths. It is therefore expected that they should be able to suggest multiple solutions. However, they are not expected to suggest as many solutions for the more difficult Tarzan Problem.

Using this framework of analyzing solution approaches is more straightforward in the case of the Ball Drop Problem than for the more difficult Tarzan Problem. For the Ball Drop Problem, the interview participants were able to discuss multiple approaches while most students were only able to discuss one approach to the Tarzan Problem. However, the students' qualitative analyses of the Tarzan Problem were much more extensive than for the Ball Drop Problem. The students' qualitative analysis activities are discussed in Chapter 7.

Results

Solutions to Ball Drop Problem

Five students initially tried to solve the ball drop problem using a kinematics approach. In addition, Kaylee initially tried a force approach, and Malcolm successfully used an energy approach on his first attempt at a solution. Each student's initial approach to the ball drop problem is listed in Table 6-2, along with relevant

Table 6-2: Students' initial approach to the Ball Drop Problem. Names are pseudonyms. Numbers refer to transcript lines.

Student	Initial Approach	Student statements	Characterization
Zoe	Kinematics [Lines 398-403]	*I got confused because we were talking about the...what was it called … projectiles, and so I got confused, but then I realized I had uhh, potential-energy and I needed a velocity, so I knew to relate those two.* [Lines 401-403]	**Novice-like**
Simon	Kinematics [Lines 6-12]	*I just figured, just dropping it and so gravity is just going to [be] acting on it, and depending on, er, I knew that it was a kinematics problem.* [Line 8]	**Novice-like**
Jenny	Kinematics [Lines 89-96]	*I wouldn't really think too much about it 'cause I've done dropping problems so much that I just know like I think its this one* (points to a kinematics equation in the reference booklet). [Line 89]	**Novice-like**
Kaylee	Forces [Lines 20-24]	*[Forces is] probably the first thing I was taught when I first started learning physics. So I just automatically think of what forces there are.* [Line 132]	**Novice-like**
Hoban	Kinematics [Lines 4-8]	*Well first I tried to remember that equation for like the position of a particle or something that was a long time ago* [4]	**Novice-like**
Malcolm	Energy [Line 249]	*So I was thinking umm, in the ball there's gravity and when you let go of the ball it is going to go down in the direction of the gravitational field and it's going to acquire energy and it's going to equal the change in potential energy* [Line 249]	**Expert-like**
Nathan	Kinematics [Line 87]	*So a lot of my current picture of this comes from the way [high school] kids do it because I tutor several of them on Mondays so equation 4 is "v"-squared minus "v nought" squared equals to "a" "s" minus "s zero".* [Line 87]	**Novice-like**

statements about this initial choice. Simon, Jenny, and Nathan all solved the problem correctly using kinematics. Zoe, Kaylee and Hoban abandoned their initial approaches and found correct solutions using an energy conservation approach. All students were able to discuss multiple approaches to the ball drop problem. Some solution approaches were suggested by the students and some were suggested by the interviewer. Table 6-3 shows a summary and characterization of the solutions suggested by the students and the solutions that the students were able to use successfully to solve the problem. Some of the successful solutions were approaches that were suggested by the interviewer.

The number of solutions suggested by the students was characterized based on the number and variety of the physics constructs involved in the solutions. The number of solutions completed by each student was similarly characterized. Three solutions using different physics constructs was judged to represent a reasonably diverse set of solutions, so that if a student is able to successfully suggest/solve the problem using three or more approaches involving different physics constructs, then the number of suggested/completed solutions is characterized as expert-like. If the student could only suggest/complete one solution, or solutions that involve similar physics constructs, the student was characterized as novice-like. Some students were characterized as being in an intermediate state of expertise.

Table 6-3: Solution approaches suggest by students and completed for the Ball Drop Problem. Names are pseudonyms.

Student	**Suggested Approaches**	**Characterization**	**Solutions Successfully Completed**	**Characterization**
Zoe	Kinematics Energy Cons. Forces	**Expert-like**	Energy Cons.	**Novice-like**
Simon	Kinematics (time-indep.) Kinematics (time-dep.)	**Novice-like**	Kinematics Energy Cons. Work-Energy	**Expert-like**
Jenny	Kinematics	**Novice-like**	Kinematics Energy Cons.	**Intermediate**
Kaylee	Forces Energy Cons.	**Intermediate**	Energy Cons.	**Novice-like**
Hoban	Kinematics Energy Cons.	**Intermediate**	Energy Cons.	**Novice-like**
Malcolm	Kinematics Energy Cons. Experiment	**Intermediate**	Energy Conservation Work-Energy	**Intermediate**
Nathan	Kinematics (time-indep.) Kinematics (time-dep.)	**Novice-like**	Kinematics Work/Energy Cons.	**Expert-like**

Malcolm suggested three approaches for finding the speed of the ball just before it hits the ground, but only two of these suggestions are analytical solutions. Although his other suggested solution, performing an experiment, represents a large and important part of the discipline of physics, the characterization of his suggested solutions was based on the two analytic solutions. It is noteworthy that Malcolm considers "performing an experiment" to be a valid response to the question and his response may be related to his experience as a teaching assistant in a physics laboratory course.

Although Nathan was only able to complete two solutions, his second solution is a mixture of two physical principles: the work-energy theorem and the law of conservation of mechanical energy. Therefore, his characterization was judged to be similar to Simon’s, who was able to complete three different solutions.

Students' Solution Preferences to the Ball Drop Problem

Each student interviewed expressed a preference for a particular solution path for the ball drop problem, as summarized in Table 6-4. Six of the students expressed a preference for the energy solution, even though most of them initially attempted a kinematics solution. Because energy is a deep and general physical principle, it is characterized to be an expert-like preference, while kinematics is characterized to be a novice-like preference. However, most of the students explained their preference by talking about the energy solution being easier to perform than any other solution paths. This reason of mathematical efficiency does not reflect an expert-like organization of physics knowledge, and is therefore characterized as being in an intermediate state of expertise.

Table 6-4: Students' preferred approach to the Ball Drop Problem. Numbers refer to transcript lines.

Student	Solution Preference [Characterization]	Student statements
Zoe	Energy Conservation [**Intermediate**]	*This one [graphical kinematics] requires a little more thinking and using time, since it relates to acceleration. Then I guess it takes a lot more thinking to figure out like, there's more equations, there's that and then umm, like velocity divided by time equals acceleration you have to relate those two together. Whereas these two [kinetic and potential energy] correspond and relate, so in this problem if one decreases then the other one has to compensate and increase. So, in this [energy] way of finding the answer everything that you need is right here. And you can just plug in numbers.* [Lines 465-473]
Simon	Energy Conservation [**Intermediate**]	*Um...the energy way, well like I have that one, I guess as far as like energy goes I kinda know these [pointing to the kinematics equations in the reference booklet] off the top of my head, but not entirely. This equation, you know "$mgh=\frac{1}{2}mv^2$" solving for velocity we've done a lot. So like, this one [pointing to the energy conservation equation] you know, I didn't even have to look [for] it. So in a way that would be kinda easier, if I, like, thought of it first.* [Lines 78-80]
Jenny	Kinematics [**Novice-like**]	*[Energy is] less obvious to use. Like actually using it isn't harder but it's easier to think about something in terms of, it's a mass and it's moving and it's changing how it's moving over some distance and to think about energy, 'cause you see you see mass and you see velocity and you see acceleration and you experience it whereas energy is happening but you are not as aware of it.* [Line 155]
Kaylee	Energy Conservation [**Intermediate**]	*I like energy better because, I mean it's conserved and it's prettier. You know that everything on one side is gonna equal everything on the other side and you won't like forget a force or anything.* [Lines 138-142]
Hoban	Energy Conservation [**Intermediate**]	*…after having learned like everything about energy conservation, it's just more intuitive just to put in the sense of the energy, the potential and the kinetic, and setting them equal. No, I use energy conservation for almost everything now I think like whenever I try and solve something I use that first.* [Lines 32-34]

Table 6-5: Students' preferred approach to the Ball Drop Problem. Numbers refer to transcript lines, Continued.

Malcolm	Energy Conservation [**Expert-like**]	*Ok, so I thought this [energy] way would avoid some math. One thing I know just from experience is that this way is faster and it's more fun using energy conservation. So it's, this is a nice, this is almost an extra, some more physics that you put into the problem. This [kinematics] is more simple and this is energy conservation, umm, so I guess this [kinematics] is too kinda boring to do it this way and here [energy] you can use a trick, kind of a different method to solve the problem.* [285-287] *I'm just saying this [energy] is additional physics that one can use it's not as obvious as perhaps this [kinematics]...* [Line 293]
Nathan	Energy Conservation [**Intermediate**]	*I didn't even think of that so, OK, work is ... so the easiest way using work-like concepts would be change in potential energy and change in kinetic energy and so you've got "mgh" equals "½ mv^2" and [darn] that's so much easier! Why didn't I do that in the first place!? So then you get "2gh" no "square root 2gh" equals "v".* [Line 185]

Malcolm identified energy as being efficient, but his discussion suggests that his preference for the energy solution also arises from its conceptual sophistication. His preference is quite strong; he said that when he grades this problem as a TA, he deducts points from students who use a kinematics approach because of its conceptual inferiority to an energy approach.

342	Interviewer:	So if you were going to grade this student on their solution...
343	Malcolm:	Ummhmm, yes…
344	Interviewer:	...like what kind of criteria would you use to grade them?
345	Malcolm:	Ok. Here I would take points off and then if he sees me and explains this to me I would give him back, but I wouldn't take too many points off because it's it he gets the right answer...
346	Interviewer:	So you take points off for not invoking energy directly here?
347	Malcolm:	Umm, yes I would, but I would give them still the I would think

		maybe this is their way of thinking and if they can carefully do this I wouldn't take too many points off, I remember exactly actually the solution that I was reading...
348	Interviewer:	Ummkay.
349	Malcolm:	Umm, I remember the solution, so so I remember if it was like 5 points I would give them I don't know somewhere 4 points 3 or four points...
350	Interviewer:	Ok.
351	Malcolm:	Umm, but I never, nobody actually came back to see me, since I remember exactly this, so...

Therefore, Malcolm’s preference for an energy conservation approach is characterized as expert-like.

Jenny is the only student who expresses a preference for a kinematics solution. She believes that kinematics is a more obvious solution path because it is more closely connected with observable quantities. When discussing an energy solution, she admits that it is not more difficult than using a kinematics solution, and she speculates that the reason she thinks of kinematics first is that she learned kinematics first.

210	Interviewer:	OK so before you were describing that there was a disadvantage to using energy which is just like its hard for you to "see" energy
211	Jenny:	Uh huh
212	Interviewer:	Right?
213	Jenny:	Yes
214	Interviewer:	Are there other disadvantages to doing it an energy way or is that really than main one?
215	Jenny:	Yes, like it’s not any harder, it’s just a different mess around with an equation
216	Interviewer:	Ok. Do you tend to use the kinematics way more than the energy way if the choice is yours?

217	Jenny:	Umm yea, I would divert to... I would go back to kinematics if it wasn't asking me for anything else.
218	Interviewer:	Ok and why do you think that is?
219	Jenny:	Umm, I dunno. I guess like what comes to mind is just that it's easier to think about but…
220	Interviewer:	Ok.
221	Jenny:	…it's always introduced to you first so you get used to doing that and then like oh there's this energy thing and you are like, yes, ok, energy. So if they ask you about energy I'll use energy but I already know this [kinematics] thing so maybe if they taught in the other order it might change things.

Jenny's reason for preferring a kinematics solution has to do with physical quantities that are involved being closely connected to the surface features of the problem. Therefore, her preference is characterized as novice-like.

Solutions to Tarzan Problem

The Tarzan Problem was a much more difficult problem for the students than the Ball Drop Problem. No student was able to suggest more than one solution path, and only Nathan (a graduate student) was able to find a correct solution. All of the students began their solutions by drawing a picture and performing an analysis of forces, except Nathan, who discussed centripetal force and energy before drawing a force diagram. Energy conservation was only brought up by students who realized that Tarzan's speed at the bottom of the arc would affect the tension in the vine, and all students who solved for the speed used energy conservation. None of the students began by looking for conserved quantities, although Nathan mentioned energy conservation fairly early in his solution and Zoe, Kaylee, and Hoban mentioned it later in their solutions.

Table 6-6: Students' initial approaches to the Tarzan Problem.

Student	**Initial Approach**	**Characterization of Approach**	**Discussed Energy?**
Zoe	Analysis of forces	**Novice-like**	Yes
Simon	Analysis of forces	**Novice-like**	Yes
Jenny	Analysis of forces	**Novice-like**	No
Kaylee	Analysis of forces	**Novice-like**	Yes (after interviewer suggests centripetal motion)
Hoban	Analysis of forces	**Novice-like**	Yes
Malcolm	Analysis of forces	**Novice-like**	No
Nathan	Analysis of forces	**Novice-like**	Yes

Table 6-7: Students' errors and solutions to the Tarzan Problem

Student	Critical Error Made in Solution	Final Answer
Zoe	Unable to apply Newton's 2nd Law – can't quantitatively relate tension and centripetal acceleration [Line 647]	Tarzan's height matters, but can't calculate a height [Lines 647-659]
Simon	Does not identify the correct acceleration [Line 206]	Thinks the height doesn't matter but isn't sure [Lines 206-214]
Jenny	Does not consider centripetal acceleration [Lines 285-295]	Tarzan's height doesn't matter [Lines 285-295]
Kaylee	Inappropriate use of Newton's 1st Law to balance tension in vine, Tarzan's weight and centripetal force. [Line 238]	$h_{\max} = \frac{l}{2}\left(1 - \frac{T}{mg}\right)$ [Lines 238, 254-260]
Hoban	Error in applying Newton's 2nd Law – set centripetal acceleration equal to the tension in the vine. [Line 124]	$h = \frac{Tr}{2mg}$ [Lines 132-138]
Malcolm	Does not consider centripetal acceleration [Line 427]	Thinks that the height doesn't matter.[Line 427-429]
Nathan	None	$h_{\max} = \frac{l}{2}\left(\frac{T}{mg} - 1\right)$ [Line 307]

Some students made errors in applying Newton's Second Law (not realizing that Tarzan is accelerating at the bottom of the swing), or in identifying forces (not realizing that the centripetal force is the same as the net force - the vector sum of the tension force and the force of gravity). Simon, Jenny, Kaylee, Hoban and Malcolm all claim at some point in their solutions that Tarzan’s initial height does not affect whether or not the vine will break. Kaylee and Hoban retract this claim later in their solution.

Students’ Discussions of Lagrangian Techniques

The interview participants who had taken a course an upper-division analytic mechanics were asked to discuss using Lagrangian techniques as a solution path for these problems. Table 6-8 summarizes the students’ discussions of these techniques. No student was able to solve either problem using this approach.

Table 6-8: Students' discussions of using a Lagrangian approach to solve the Ball Drop and Tarzan Problems. Names are pseudonyms.

Student	**Able to use Lagrangian Approach?**	**Illustrative Statement**
Kaylee	No	*Yeah, all those and it's a lot more mathematical. It's like you have to figure out how to start the problem and then once you do it's a whole bunch of math... but the hard part is starting the problem, and yeah.* [Lines 150-152]
Hoban	No	*Whenever I did Lagrangians I messed up the coordinate systems … and got them confused ... so if I don't have to use it I don't.* [Line 208]
Malcolm	No. Outlined a solution for Tarzan Problem	*I think it's, the Lagrangian is the kinetic energy minus the potential energy and they want to find a path that minimizes this, umm ok and then we have the Lagrangian equation we can use the coordinates ok so this could be coordinate 'x', yeah, so I wouldn't know how to do it right now but I think that you can definitely use that.* [Line 315]
Nathan	No.	*Lagrangian mechanics is so much wrapped up in mathematics, umm that I understand and I think like I, I don't think I mentioned already, its one of those things that I understand I have a physical intuition for the starting point and then a bunch of mathematical [stuff] to get the tool at the end. So I understand that the action is minimized between two points and minimization of the action is minimization of the Lagrangian and then there's a bunch of math from there that involve velocity-like things and position-like things. It's all kind of vague and… but, er, yeah, interesting. I never ... I... it's such a powerful tool and I enjoyed it so much when I learned it, but boy it's totally irrelevant.* [Line 251-253]

Kaylee described Lagrangian techniques as "weird" and highly mathematical, although she identified them as being related to force and energy techniques. She said the most difficult part of solving problems in her upper division mechanics course is figuring out how to start the solution.

145	Interviewer:	Ok. Do you use energy conservation a lot in your classes now?
146	Kaylee:	Now? Probably less. Now we do weird things.
147	Interviewer:	Weird?
148	Kaylee:	Things.
149	Interviewer:	Like Lagrangian type things?
150	Kaylee:	Yeah, all those and it’s a lot more mathematical. It's like you have to figure out how to start the problem and then once you do it's a whole bunch of math...
151	Interviewer:	Right.
152	Kaylee:	...but the hard part is starting the problem, and yeah.
153	Interviewer:	Do you, do you see Lagrangian mechanics as being kinda separate from the force and energy stuff that you were doing last year?
154	Kaylee:	Not really separate, it's a different way of looking at it.
155	Interviewer:	What do you mean?
156	Kaylee:	Like, I guess not really separate because energy's in there, in the equation, so, yeah it's not that separate.
157	Interviewer:	Umm-kay.
158	Kaylee:	It's just, yea, another way to unify everything I guess.

Although Kaylee’s discussion was fairly general, she demonstrated some conceptual understanding of Lagrangian methods by indicating that the Lagrangian is related to energy.

Hoban was asked about using Lagrangian techniques to solve the Tarzan Problem. At first he said that those techniques are too complicated for this problem, meaning that it would take more steps than his original force approach [Line 198]. He then characterized the Tarzan Problem as being simpler than the problems he typically encounters in the mechanics course he was taking at the time (“There is just less things to keep track of -- like less moving parts I guess.” [Line 202]) He explained that although he couldn't use them to solve this problem, he expected that Lagrangian techniques would be easier than his force approach. Like Kaylee, Hoban is uncomfortable using Lagrangian techniques. Hoban explained that he often makes mistakes using generalized coordinates and because of this difficulty, he tries to avoid using Lagrangian techniques.

190	Hoban:	Err, there might be others, but this [force way] is probably the best way... so no, I can't think of another way [to solve the Tarzan Problem] right now.
191	Interviewer:	So, if you were going to try to start to think about another way, what kinds of things would you think about?
192	Hoban:	Err … I think about a force diagram I guess I could try ... I think that would be the only way I could start it.
193	Interviewer:	Ok. What about thinking about Lagrangian stuff?
194	Hoban:	Yeah, yeah, that's probably too complicated for this.
195	Interviewer:	Why, why do you say that?
196	Hoban:	It seems like it would be.
197	Interviewer:	What do you mean by "too complicated"?
198	Hoban:	Umm, I think it would take more steps.
199	Interviewer:	OK, So how is this problem different from the kinds of problems that you are seeing in 110B? 110B is mechanics, right?
200	Hoban:	Yes. Well it's like simpler but I guess not easy.
201	Interviewer:	What do you mean by simpler?
202	Hoban:	There is just less things to keep track of -- like less moving parts I guess.
203	Interviewer:	Do you think I could rephrase the wording of the question that would make you more inclined to doing it in a Lagrangian way?
204	Hoban:	Err, probably, yeah, umm, I guess ... I suppose I haven't used enough Lagrangian to just use it whenever I can
205	Interviewer:	Oh, ok.
206	Hoban:	But it probably would be easier that way.

207	Interviewer:	So you think it would be easier to do it in a Lagrangian way?
208	Hoban:	Probably, ‘cause the ones I've done it was like, I don't know ... it came up pretty smart so … I could probably figure it out and get the tension. Whenever I did Lagrangians I messed up the coordinate systems … and got them confused ... so if I don’t have to use it I don’t.
209	Interviewer:	Ok, so last quarter you did Lagrangians, and this quarter are you still doing Lagrangians?
210	Hoban:	Umm, a little bit, like right now we are doing moments of inertia for rotating bodies and stuff like that.
211	Interviewer:	Ok, but you did a little bit of Lagrangian stuff at the beginning of the quarter?
212	Hoban:	Yes, it came up again in … umm... something… it did come up again

Hoban talked about Lagrangian techniques in a very general way. There is little evidence to indicate his conceptual understanding of these techniques.

Malcolm discussed Lagrangian techniques twice during the interview. For the Tarzan problem, he recognized that those techniques would yield a solution and his discussion showed some understanding of how those techniques could be used, though he could not perform the necessary computations.

314	Interviewer:	Ok, what about using Lagrangian techniques to solve this problem?
315	Malcolm:	Umm-kay so lets see, Lagrangian techniques, what do they say, they say that umm, ummkay they wanna minimize the I think it’s, the Lagrangian is the kinetic energy minus the potential energy and they want to find a path that minimizes this, umm ok and then we have the Lagrangian equation we can use the coordinates ok so this could be coordinate 'x', yeah, so I wouldn't know how to do it right now but I think that you can definitely use that.
316	Interviewer:	Ok.
317	Malcolm:	To do that, yeah.

Malcolm also discussed Lagrangian techniques in the context of the Tarzan Problem. He outlined how the solution would proceed, and then compared it to the force/energy conservation approach used in the sample solution.

492	Interviewer:	So do you think that it would be wise to use a Lagrangian method to try to solve this problem?
493	Malcolm:	Ok, so umm, would be wise, yea. Umm so what are we solving? We are trying to find ok when it when it lets go, so we need forces, uhh, not sure my first thought is that it wouldn't be so good since Lagrangian gives us equation for, for, umm, the speed and for the position so yeah ok we can, we need still the these forces here so we need to consider forces for this problem and the Lagrangian I think bypasses the forces so I'm not sure it would be too useful.
494	Interviewer:	Ok.
495	Malcolm:	Unless we do this and then use the Lagrangian to find 'v' which is I think unnecessary. Then plug it in but I think we need, my impression is that we need to write this what he has here.
496	Interviewer:	What do you mean it's unnecessary?
497	Malcolm:	Ohh ok, so I think the Lagrangian will…will…the equation would give us umm, would give us 'x' the position in time and it would also give us the velocity in time...
498	Interviewer:	Ummkay.
499	Malcolm:	...but we really are concerned, need force here...
500	Interviewer:	Ok.
501	Malcolm:	....so, so umm pretty much I think you're going to have to do this equation and would feed it here...
502	Interviewer:	Ok.
503	Malcolm:	...and the 'v' is very simple to find 'v' that we plug in here [pointing at the sample solution], to see that he found 'v' and he plugged it in...
504	Interviewer:	To energy conservation right?
505	Malcolm:	Right he used energy conservation to find 'v' so that he can plug it in to calculate this force, umm from which he calculates later on.
506	Interviewer:	Ok.

507	Malcolm:	… so I don't see why it would be a good idea to use this.

Malcolm did not solve either of these problems using Lagrangian techniques, but he could plan solutions using Lagrangian techniques (by considering the given quantities are and the quantities that Lagrangian techniques yield). He did not describe the mathematical difficulty of the approach, nor did he express discomfort using them though he did admit that he was unable to use this approach during the interview.

Like Malcolm, Nathan could not remember specifically how to make computations using Lagrangian techniques and his discussions show that he has some general understanding of Lagrangian mechanics. He was asked to consider Lagrangian techniques as an approach to the Ball Drop Problem.

238	Interviewer:	Ok so I'm gonna try to stretch your brain a little bit further. Would you ... or could you try to solve this problem using Lagrangian mechanics?
239	Nathan:	Heh-heh..... er do I get to cheat and go look up what I want?
240	Interviewer:	Oh, yeah.
241	Nathan:	Umm ... er ... yeah I would have to look up how the Lagrangian works again because I don’t remember, um… do you want me to?
242	Interviewer:	Well ... sure I don’t have Marion and Thornton here, I've got Goldstein though, but which equation do you want? Do you know which equation you want?
243	Nathan:	No, I would have to open it up to the ... is this worth doing do you think?
244	Interviewer:	Er, maybe not.
245	Nathan:	Probably not.
246	Interviewer:	Maybe not.
247	Nathan:	Yeah, I'd have to look stuff up umm because its not something that I remember how to do
248	Interviewer:	What do you remember about Lagrangian mechanics?

249	Nathan:	(both much laughter)
250	Interviewer:	I ask because I opened my textbook up the other day and I was thinking like "man how much of this do I remember and what do I really understand in a physical way like I understand Newtonian mechanics?"
251	Nathan:	Er ... yeah, the Lagrangian mechanics is so much wrapped up in mathematics, umm that I understand and I think like I , I don't think I mentioned already, its one of those things that I understand I have a physical intuition for the starting point and then a bunch of mathematical [stuff] to get the tool at the end. So I understand that the action is minimized between two points and minimization of the action is minimization of the Lagrangian and then there's a bunch of math from there that involve velocity-like things and position-like things. It's all kind of vague and…
252	Interviewer:	Ok
253	Nathan:	…but, er, yeah, interesting. I never ... I... it's such a powerful tool and I enjoyed it so much when I learned it, but boy it's totally irrelevant.
254	Interviewer:	Why do you say it's a powerful tool?
255	Nathan:	'Cause I could solve problems ... I could solve ridiculously abstract beads on strings particles with it that I couldn't do otherwise
256	Interviewer:	Ok, but what about for this problem? Is Lagrangian mechanics a powerful for this problem?
257	Nathan:	Umm, that is an excellent point it's kinda like using ... using the cow knife to kill a chicken - I had a Chinese math teacher. (both laugh)
258	Interviewer:	Ok, so by that you mean it is too powerful of a tool to be used for this problem?
259	Nathan:	It's just so much unnecessary work 'cause I'd have to remember how the [heck] it works and then you would have to set it up but this one you know I could just pull the answer out more or less.

Like Kaylee, Nathan characterized Lagrangian techniques as mathematically involved. He said he has some conceptual understanding of how to start using this approach, but making progress beyond that involved mathematical computations without conceptual understanding. Nathan also recognized these techniques as useful for some abstract, complex problems (like beads on a string). He described Lagrangian techniques as “powerful” and “totally irrelevant” in the same sentence. In the case of the Ball Drop Problem, he judged it an unnecessarily difficult approach.

In summary, no student solved either problem using a Lagrangian approach. Kaylee and Nathan discuss having a lack of conceptual understanding of the details of Lagrangian mechanics. Although Hoban does not specifically discuss his level of conceptual understanding, there is little evidence of any conceptual understanding in his discussion. Malcolm’s discussions of Lagrangian mechanics are the most suggestive of conceptual understanding, but this understanding is about the larger characteristics of this approach – which quantities are needed to use the approach and which quantities the approach will yield in the end. As in the case of the other interview participants, there is little evidence to suggest that he conceptually understands the details of a Lagrangian approach.

Discussion of Students’ Solutions

In looking at the students’ solutions, each student is found to be in a mixed state of expertise, with some aspects being expert-like and some novice-like. Table 6-9 shows a summary of the characterizations made about the students’ initial solutions, suggested solutions, completed solutions, and preferred solutions for both the Ball Drop and Tarzan problems.

Table 6-9: Summary of Characterizations of Students' Solutions

Student	**Ball Drop Problem**				**Tarzan Problem**
	Initial Approach	Suggested Approaches	Successfully Completed Approaches	Solution Preference	Initial Approach
Zoe	Novice-like	Expert-like	Novice-like	Intermediate	Novice-like
Simon	Novice-like	Novice-like	Expert-like	Intermediate	Novice-like
Jenny	Novice-like	Novice-like	Intermediate	Novice-like	Novice-like
Kaylee	Novice-like	Intermediate	Novice-like	Intermediate	Novice-like
Hoban	Novice-like	Intermediate	Novice-like	Intermediate	Novice-like
Malcolm	Expert-like	Intermediate	Intermediate	Expert-like	Novice-like
Nathan	Novice-like	Novice-like	Expert-like	Intermediate	Novice-like

In looking at individual students across the various solution aspects (looking along the rows of Table 6-9), Malcolm has the most expert-like characterizations and Jenny has the most novice-like characterizations, though there is no clear trend of increased expertise with increased experience for these students. In contrast, clearer trends are found by looking at the various solution aspects across students (looking down the columns). The initial solution approaches to both problems are the most novice-like and the students' preferences are the most expert-like. These trends suggest that the interview participants have values that are similar to those of experts (they prefer the same types of solutions) but access their knowledge differently (based on the order learned in the case of the ball drop problem and in a working-backward manner in the case of the Tarzan Problem).

Surprisingly, a student's initial approach to the ball drop problem was generally different from the student's preferred approach. A student's preferred approach was most commonly the approach that was perceived as the easiest: solutions that were more conceptual and required fewer mathematical manipulations. Some students discussed the degree of abstraction of the core concepts involved in the solution: Jenny preferred quantities closely connected to observables and Malcolm preferred more abstract quantities that required more thinking. The students' preferences for an energy approach are consistent with observations of experts, who on difficult problems try to use conservation principles before resorting to other approaches [57]. Yet, even though several students discuss using energy conservation in a multitude of contexts, most students did not initially try energy methods to solve the ball drop problem.

The most common reason suggested by the students for their initial choice of approach is that it was the first approach learned for this type of problem.

> **Simon** [Line 74] "*maybe because it's been like the first way we learned*"
>
> **Jenny** [Line 221] "*[kinematics is] always introduced to you first so you get used to doing it that way*."
>
> **Kaylee** [Line 132-134] "*[the force approach is] probably the first thing I was taught when I started learning physics. So I just automatically think of what forces there are.*"
>
> **Hoban** [Line 10] "*[kinematics is] how I learned it, like, the first time. Like, I remember all the projectile problems and you setup this thing and then you figure it out from there*."
>
> **Nathan** [Lines 287-289] "*I think a lot of it, a lot of it is your initial perception of a concept really jades your appreciation of that concept so… So because my initial perception of physics and these problems is through kinematics that's why I do it that way I think.*"

Additionally, although Zoe does not suggest this factor explicitly for her initial approach (kinematics), she explains that when she is confused about how to use an energy approach, she will fall back on a kinematics approach because it was the first thing she learned [Lines 413-417]. These explanations suggest that in solving this problem, the relevant physics information was accessed by many students according to chronology rather than conceptual hierarchy, a novice-like practice [60]. In contrast, Malcolm used an energy conservation approach even though he mentions that the first approach he learned for this problem was kinematics [Line 297].

All of the interview participants began their solutions of the Tarzan Problem by analyzing the forces acting on Tarzan. This approach is characterized as novice-like due to the fact that experts are likely to approach difficult problems by looking for conserved quantities. By analyzing forces, the interview participants' approach is suggestive of a means-ends analysis (because the critical criterion for the problems is the tension in the vine). Solving the problem this way is a more direct approach. Most of the students recognized that mechanical energy is conserved in this problem, although this did not become important in their solutions until after the forces were analyzed.

Another striking occurrence was that some students were able to successfully complete solutions that they did not suggest themselves. For example, after Jenny solves the Ball Drop Problem using a kinematics solution, she says that she cannot think of any more solutions.

98 Interviewer: Ok. Can you think of any other ways that you might solve this problem? Like different methods?

99 Jenny: Maybe. I've just done it this [kinematics] way so many times umm lets see ... pause .. not without getting like ... I'm sure like you could find some other obscure way to do it but it seems like you'd just make it way more complicated than you would need to

After some discussion, the interviewer suggests using energy conservation. Jenny completes this solution successfully and discusses having used this solution in the past. Similar incidents occurred for the Ball Drop Problem during the interviews with Simon, who successfully completed energy and work solutions, and Nathan, who successfully completed an energy solution.

49 Interviewer: Ok. Um, what about using conservation of energy to solve this problem?

50 Simon: Um, yeah I could. Um, I don't know, I think of using those more for ramp problems.

In all of these cases, the solution had been suggested by the interviewer. These students clearly possess the knowledge necessary to complete the suggested solutions, but this knowledge is not accessed when trying to formulate a solution themselves. This task of finding multiple solutions to a single problem is uncommon in physics courses, and these students probably have little experience considering physics problems in this way.

293 Nathan: I generally go with the first solution that comes to my mind ... err ... well I think it depends on the problem. It depends on, yes, it depends on the problem ... er ... looking at, er ummm… no I just run with my first impression.

294 Interviewer: Ok

295	Nathan:	Anything else I would say would be more speculation mostly I try the first thing that comes to me and when that doesn't work I back up and try something else.

Many of these physics majors demonstrate an ability to use physical intuition to solve physics problems. One way experts use physical intuition is to map a given problem to a similar, familiar situation. Novice problem solvers cannot as easily match problems with known solutions because of their limited experience solving physics problems. Many of the interview participants chose their initial approaches to the Ball Drop Problem by recognizing the problem and remembering a known solution path. In this way, their approach is consistent with using physical intuition in their solutions. Although the use of physical intuition is considered an expert-like practice, these students were strongly influenced by the context of the problem - they remembered solving this particular problem first using kinematics. As a result, their intuition did not always lead to a solution path that they could complete (i.e. they couldn’t remember the appropriate equations) or to their preferred solution.

Although this is a small sampling of physics students, it is somewhat surprising that none of the more experienced students is comfortable using Lagrangian techniques in solving these problems. Kaylee and Hoban have studied this material more recently than Newtonian mechanics, and Nathan has studied it twice – once as an undergraduate and again during his graduate studies. Nonetheless, all of these students have passed at least one course that covered Lagrangian mechanics, and it was therefore expected that they would be able to demonstrate Lagrangian techniques.

A well-established result from cognitive science [74] is that information in long term memory is easier to retrieve if it is encoded by meaning (encoded semantically). This helps to explain why these students have difficulty remembering the procedures of a Lagrangian approach – the procedures have little conceptual meaning to them.

Although there is an increased PER interest in upper division physics coursework, no studies have focused on students' ideas about Lagrangian mechanics. The interview participants' discussions raise general questions about what students learn in upper division mechanics courses and why these courses are taught. Perhaps the utility of these courses is that students learn of the existence of these techniques and get some experience using them, rather than achieving proficiency. Another possibility is that students practice the important research skill of grappling with complex techniques that (at least in the beginning) they do not understand. Clearly more focused research needs to be done in this area. This research can help physics departments discuss how the learning goals of such courses fit in with the broader learning goals of undergraduate physics programs.

A Closer Look at Expert/Novice Distinctions

In the framework used to characterize the problem solving expertise of physics majors, the problem solving activities of the interview participants were compared to observations of expert and novice problem solvers. As a result, the kinematics solutions of the Ball Drop Problem and the force analyses of the Tarzan Problem were categorized as novice-like approaches. However, the question remains, does this novice-like characterization mean that these approaches are unsophisticated?

Their choice of a kinematics approach to the Ball Drop Problem is based on their physical intuition. According to Newell & Simon's [75] definition of a "problem" ("A person is confronted with a *problem* when he wants something and does not know immediately what series of actions he can perform to get it"), what these students are doing may be more appropriately characterized as an *exercise* – demonstrating an ability to perform a known series of actions to compute the answer. These students may not have known the answer, but they already knew the solution. The same is true for experts when they solve similar problems - the experts generally already know the steps needed to find the answer. However, experts' intuitions lead them to look for conserved quantities, whereas these students generally began with kinematics.

Furthermore, the novice-like characterizations were based on the fact that generally experts try an energy approach first, but there are no data to show that experts would choose an energy approach for these specific problems. In fact, Nathan, an advanced graduate student, has a similar experience level to people who have been used as experts in other problem solving studies. His "novice-like" initial approaches raise questions about how other "experts" would approach these specific problems, especially experts who, like Nathan, are teaching introductory physics. One of the reasons that looking for conserved quantities is a good heuristic is that it is a way to make progress in many different situations. Since another characteristic of expertise is having a lot of domain specific knowledge, it could be argued that using a known solution is an expert-like approach.

An important difference between experts and novices is their different roles and motivations. Experts are typically teachers while novices are typically students. Many students discuss time pressures and deadlines as being important influences in their studies. Typical physics exams require students to work quickly. These factors encourage problem solving habits that are time efficient.

171	Interviewer:	So are you ready to look at somebody else's solution now?
172	Hoban:	Sure
173	Interviewer:	OK
174	Hoban:	It took too long
175	Interviewer:	It took too long?
176	Hoban:	Uh huh
177	Interviewer:	Do you usually not spend so much time?
178	Hoban:	It shouldn't be that complicated! I had the wrong formula or something

Using a known solution or beginning with a means-ends approach may be desirable in a situation where time efficiency is an important consideration. In contrast, experts are more strongly motivated to get correct answers, even if it takes a little longer to make sure the answers are correct (if they gave an incorrect response, their status as experts could be called into question). This may explain why experts have been observed to check their answers by using more than one approach [60]. Taking these motivations into consideration, it may be appropriate to characterize these physics majors as "expert physics students" compared to typical introductory students though they may be described as novices when compared to physics professors.

Conclusion

With respect to the solution paths for these two problems that were suggested, completed, and preferred, these physics majors are in a mixed state of expertise. Their preference for energy conservation as a solution for the Ball Drop Problem and their ability to use physical intuition are consistent with expert problem solvers, but their initial approaches and their difficulty in thinking of multiple solution approaches are more aligned with novice problem solvers. For the familiar Ball Drop problem, which could be described as one of the archetypal physics problem, the interview participants often chose a solution approach that was different from their preferred approach. Most students speculated that the structure of the curriculum (i.e. the order in which the physics topics are taught) influenced their solution choice. Unlike previous observations of experts, most students did not seek conserved quantities as an initial problem solving approach for either the Ball Drop or Tarzan problems.

Chapter 7: Problem Solving Heuristics

In this chapter, the problem solving interviews are further analyzed by looking at the extent to which the interview participants engage in various problem solving heuristics, including both plug-n-chug and qualitative analysis activities. Heuristics are general problem solving activities that are used in finding a solution, but do not guarantee a solution or outline an entire solution. In solving physics problems, one of the major expert-novice differences is that experts tend to perform a thorough qualitative analysis while novices tend to use equation-based techniques [51, 57, 58]. Qualitative analyses include activities like visualization, problem categorization, making analogies to familiar situations, performing a dimensional analysis, making simplifying assumptions, and considering limiting cases [53, 57, 76-78]. Equation-based "plug-n-chug" techniques exclude visualization or any conceptual considerations of the physical principles that are applicable to the problem situation. Equations are selected early in the solution and are chosen on the basis of variable matching.

Physics majors, who are more experienced physics students than typical introductory physics students, are expected to engage in some of the qualitative analysis activities that experts use, but are also expected to sometime use plug-n-chug techniques. The goal of this analysis is to determine which qualitative analysis activities are most commonly used by physics majors, which qualitative activities are physics majors uncomfortable using, and under what circumstance do physics majors use plug-n-chug techniques.

The data reported in this chapter consists of the students’ self-reported problem solving practices and observations of their problem solving activities during the interviews. Solutions to both interview problems were considered in this analysis, as well as the students comments about the sample solutions (included in Appendix V) and their elaborated responses to CLASS. The interview transcripts were coded by looking for incidents when students seemed to be using plug-n-chug techniques or any of the qualitative analysis activities described above. Because expert-novice differences have not been reported, the students’ problem solving heuristics were not analyzed with respect to an expert-novice framework. Instead, the interview participants’ use of these heuristics is described and the role of these heuristics in the students’ problem solving is discussed.

Plug-n-Chug Strategies

“Plug-n-Chug” is a type of problem solving strategy that involves means-ends analysis. A student employing a plug-n-chug strategy starts by identifying the quantities that are given in a problem and the quantity that they are asked to find. They then look for an equation that contains the given quantities and the only unknown quantity is the one they are asked to find. This process is also known as equation hunting. A hallmark of a plug-n-chug strategy is that it excludes consideration of the applicability of the equation to the problem situation or the physical meaning of the equation. Instead, variable matching is the primary consideration.

During the interviews, there was little evidence that the interview participants were employing a plug-n-chug strategy. Simon, Jenny and Hoban engage in activities that on the surface appear to be plug-n-chug, but their specific thought processes while doing these activities remain unknown. Simon appears to use a plug-n-chug strategy during his first solution to the Ball Drop problem. He listens to the questions, draws a picture that represents the known and unknown quantities, and then looks through the reference booklet to find the equation that he needed. Jenny too appears to use a plug-n-chug strategy for the Ball Drop problem.

93	Jenny:	OK is this the right equation? Oh that's not an equals sign, I think that's what it is, but I'm guessing it would be in here (checks crib sheets) so I can check. I tend to check things before I like go though the whole problem and find out my equation was wrong.

In both of these cases, Simon and Jenny knew what equation they were looking for. They claim that they "wouldn't need to think too much about it" because they had already done the problem many times.

On the whole, Hoban does not employ a plug-n-chug strategy when solving the Tarzan problem, though he does look up the equation for radial acceleration in the reference booklet. He does not make any statements that demonstrate an understanding of centripetal acceleration, and he makes an error connecting the centripetal acceleration with the forces acting on Tarzan. This error could indicate that Hoban is not thinking about centripetal acceleration in a conceptual way, but it could also be interpreted as Hoban having a misconception about centripetal acceleration or it could be an error in applying Newton's 2nd Law.

The strongest evidence against these students' use of plug-n-chug strategies during the interviews are the students' discussions of physics concepts related to the problems. Most students were able to demonstrate some conceptual understanding of the solution approaches they discussed. Table 7-1 contains some of the evidence of this conceptual reasoning.

Table 7-1: Evidence of conceptual reasoning in students' discussion of the interview problems. Direct quotes from students are italicized.

Student	Ball Drop Problem	Tarzan Problem
Zoe	*So I know that, umm it's been a while. So...I know that the ball has a certain GPE...Which is mgh, and at that point it has no velocity, and I know that at the end of the problem it will so I know to relate it to kinetic energy, and there will be no potential energy at the end of the problem.* [Lines 367-369]	*So, I would assume that at the top, since you feel the same kind of feeling that the normal force would be zero or less here, and there would be more normal force here...which means that, I guess there's more normal force here, so that should be greater here, and if it relates to...umm, how fast he's going and he's going in a circular motion. And then I'm not quite sure how we relate tension but I know that umm, a bigger acceleration would make this tension bigger...*[Lines 637-641, 647]
Simon	No discussion of concepts for the kinematics solution. *Um, so I knew work is the change in kinetic energy, and then so that's when I had to think about, ok what's , uh, doing work here? and so, the only thing I could think of is gravity, and so work is force times a distance, and so I was thinking about force, so it would have to be the mass times gravity times distance, which is bas...kinda like, basically like "mgh"* [Line 88]	*But, in this situation, I feel like for force, the mass times acceleration. And acceleration would be because of gravity which shouldn't change. So, to me it seems like just if he was holding it, and it does not break, swinging wouldn't break it either.* [Line 206]
Jenny	No discussion of concepts for the kinematics solution. *The work ... 'cause the work to lift it up should be the same as the potential energy after you lift it up.* [Line 183]	*so the tension should just balance that 'cause there's no other forces. you have a rope and you pull on it and you are just going to balance that force so that you are not accelerating and the rope is not accelerating.* [Lines 279, 285]

Table 7-2: Evidence of conceptual reasoning in students' discussion of the interview problems. Direct quotes from students are italicized, Continued.

Kaylee	*And then I thought about the forces and then I realized it would be easier just to do the energy so you have the potential energy plus the kinetic energy, kinetic energy is zero at the top. And potential energy at the bottom is zero, so mgh equals one-half 'm' 'v' squared.* [Line 20]	*I'm thinking the tension is going to have to be equal to force-gravity, but that can't be right because then it wouldn't depend on...his velocity.* [Line 184]
Hoban	*after having learned like everything about energy conservation .. just more intuitive just to put in the sense of the energy the potential and the kinetic and setting them equal* [Line 32]	*If he swings down this way then when he is at the very bottom the only force that is acting on the rope is going to be from gravity which is due to mass cause the velocity is all gonna be normal so its not going to contribute to the tension... I'm thinking that it should* [Line 94]
Malcolm	*So I was thinking umm, in the ball there's gravity and when you let go of the ball it is going to go down in the direction of the gravitational field and it's going to acquire energy and it's going to equal the change in potential energy, umm which is going to be 'm' 'g' times the difference in the distance which is 'h' and all that is going to go into the kinetic energy of the ball which is 1/2 'm' 'v' squared that I just mathematically written.* [Line 249]	*Ok, so here there is no movement along, along this direction and whenever there is no movement along a certain axis then all the forces the net force is that are parallel to that direction have to be zero. And so there's this force 'mg' cosine theta and there has to be a force that opposed it for him not to go along this direction. Umm thats why I consider this force equal.* [Line 433]
Nathan	*…the acceleration and the distance and those are the only relevant quantities for the speed of the ball at the end of the day. They are the only variables that affect the outcome I mean changing the mass of changing the color or changing the number of bananas that are taped to either ball don't change anything so its the only things that affect the outcome that I could change to change the outcome would be the acceleration and the distance.* [Lines 93-95]	*No, I figured I'ts gonna be at the bottom because the change of potential energy is the highest that's the assumption that I started with. Because that gets you the velocity and the velocity is what the rope is gonna be experiencing by way of the centripetal motion.* [Lines 369-371]

The interview participants made general comments about plug-n-chug strategies while discussing CLASS Item # 8 (“When I solve a physics problem, I locate an equation that uses the variables given in the problem and plug in the values.”). Despite a lack evidence of the students using plug-n-chug strategies to solve the interview problems, some of the students say they use plug-n-chug strategies in some cases.

139	Zoe:	Umm, number eight when I first start to learn a problem or a new concept and I'm unclear about it I'll try and do this, but if I'm really well versed and I understand it completely then I'll start doing, like I won't look for the equation, I'll like think about the problem itself and what they're asking me for and.. like for kinematics everyone goes to umm like, umm PE to KE I don't look at the equations, I start like ok well this object is gaining kinetic energy as it's losing kinetic energy and it kinda sets the problem for what its doing...
140	Interviewer:	Ok.
141	Zoe:	And then like on now what equations do I use or what would make sense in this problem, whereas if I didn’t know I'd be like ok well I know they are asking for GPE ahh and kinetic energy, and so I try an fit it together...
142	Interviewer:	Ok.
143	Zoe:	So it depends on umm, how well I understand the concepts and how well they apply.
144	Interviewer:	So, in your mind this “locate an equation” phrase means like looking up in a book, or on an equation sheet or something.
145	Zoe:	Yeah, or somewhere. Where I'm like uhh I don't know what this problem means but I'll try to find an equation that fits the information that they're givin…that they're giving me, on a test...umm, you know...

435 Interviewer: Alright so eight: 'When I solve a physics problem I locate an equation that uses the variable used in the problem and plug in the values.'

436 Kaylee: Yea.

437 Interviewer: Yea?

438 Kaylee: I, yea it's better if you have an equation that has what you're looking for and go with that.

439 Interviewer: Ok.

440 Kaylee: Yea, that’s, that’s a good starting point.

441 Interviewer: Ok.

442 Kaylee: I think, so…

443 Interviewer: So…

444 Kaylee: I don't just plug in but...

445 Interviewer: What do you mean?

446 Kaylee: Like if I see an equation that has two of the variable I need err, two of the variable I have, I won't just plug it in without making sure it applies in that situation, I won't like blindly plug it in, I’ll, you know make sure it actually applies I guess.

447 Interviewer: Ok, alright.

448 Kaylee: But yea, looking for equations that have the variables is a good way to start I think.

224 Interviewer: OK so #8 " When I solve a physics problem I locate an equation uses the variables given in the problem and plug in the values"

225 Hoban: Yeah, I try to do that whenever I can.

226 Interviewer: OK, So do you do that at the same time that you are thinking about the physical principles, or do you do these two activities separately?

227 Hoban: It really depends on the problem. Like some problems it's obvious they just want you to plug into a formula, but in some it’s not so obvious and you just have to think about it and so and with those

		its just its more thinking like cause a lot of the problems are just geared to plugging into the equation, you just put the pieces together and solve it ... but for other ones its you can't just plug it in and work it that way, you have to think about it some

Zoe, Kaylee and Hoban admit that there are times when they find plug-n-chug useful. All three of these students say that the usefulness of plug-n-chug depends on the problem. Zoe says it depends on if she can identify concepts that can be used to solve the problem. Kaylee's description of plug-n-chug is slightly different from the definition used to analyze the interviews, as hers includes a consideration of whether the equation is appropriate to the problem situation. What she describes as plug-n-chug could also be described as equation hunting. Hoban says that some problems are meant to be solved using plug-n-chug strategies.

In contrast, other students describe their problem solving as being largely absent of plug-n-chug strategies.

361	Interviewer:	What about, ah, number 8? "When I solve a physics problem I locate an equation that uses the variables given in the problem and plug in the values."
362	Simon:	I said strongly disagree.
363	Interviewer:	[Interviewer laughs] ok
364	Simon:	Because, that's maybe what I first did first doing like high school physics, cause you know basically, it was very rare that well, that they would give you a problem that you, well, that they wanted you, wanted me to like express in, ah, in general terms. So if you given like a certain, ah, you know, certain numbers, you're like, ok, I'm given a velocity, a mass, you know, then you can kinda eliminate things in your mind, like, ok I need to do, do this. But, yeah, definitely like, if we were like doing homework problems and stuff, that's definitely not the case, and, maybe, when I used to ah do problems, I'd, like a conservation of energy problem, I would be given a mass even though it's not necessary, and I know

that it ends up canceling out later on in the problem.

365 Interviewer: Ok

366 Simon: So, now I kinda expect, um, if I'm not given something that it'll, that it might end up cancelling out...

367 Interviewer: uh-huh

368 Simon: or they want me to express it in general terms.

369 Interviewer: Ok. So, when you're reading this...the way that this is worded, you're thinking of like, looking in the back of the book for an equation that has all the variables, or how like, what do you think they're talking about? And, like, plugging in numbers, or plugging in values?

370 Simon: I, yeah, I imagine them seeing, like um, like dropping a ball problem, and thinking, like ok, and then being given, well they know "g" but then being given like, um, well, like in this problem, given ah, final velocity. So, they're like, ok, well I have these things, how do I plug it in to one of these problems.

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398 Jenny: Umm, I feel that I did this when I first started physics like in my high school class, because it was like oh I am looking its you know you think of it in terms of just a math stand point like, “Oh I'm looking for x and I have y and z ,so where's something that gives me x,y,and z where I can put these in and find the answer?”

399 Interviewer: OK but you don't do that any more?

400 Jenny: But no, I think I feel like umm to an extent I think people will always do this if they are just like, “Oh I know this equation” and that you know especially if you get to the point where you just have a lot of equations in your head 'cause you use them so many times.

401 Interviewer: OK

402 Jenny: Umm, but I feel like especially as they are getting more complex that you're not just looking for some equation you are looking for a method to solve the equation.

403 Interviewer: OK, so in your mind the word "locate" isn't talking about only flipping through a book, its also, “locate” also means like thinking and recalling from memory.

404 Jenny: Hmm…

405 Interviewer: Is that true?

406 Jenny: I don't know I didn't think about it. I mean I, when I think my inclination is when locate is like, “Oh, go look it up,” but if its in your head and you are just saying “Oh this equation equates these quantities” and you are just using the equation, you are not really doing anything different than if you said, “Oh here's this equation” and used it, it seems like. The only reason its in your head is because you've used it so many times you don't need to look it up any more. So I guess like it would make sense for those to be the same thing.

407 Interviewer: OK, so how would you answer number eight? Would you agree, disagree, strongly?

408 Jenny: I would probably disagree. I don't think it’s a strongly because I don't think I can say I never just look up an equation but I think there is more that goes into it than just like just looking up the equation.

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514 Interviewer: "When I solve a physics problem I locate an equation that uses the variables given in the problem and plug in the values" now you chose strong disagree...

515 Malcolm: Ohh yea.

516 Interviewer: Why?

517 Malcolm: I don't locate an equation I try to umm, kinda try to remember the equations by just understanding physics, umm…

518 Interviewer: So when you are reading this you think of locate as looking through the textbook to find an equation?

519 Malcolm: Yea that’s what I meant. Yea that’s what I thought by 'locate' yeah.

520 Interviewer: Ok.

521 Malcolm: Umm let’s see so...

522 Interviewer: Are there any times...

523 Malcolm: ....and also plugging in the values that sounds kinda like you're

		not thinking much about it so....
524	Interviewer:	Ok.
525	Malcolm:	...and I think I have to think about it so...
526	Interviewer:	Are there times when you, when you do this or do you always think about the underlying principles?
527	Malcolm:	Well if the problem is very straightforward and you don't really think about it since it’s kinda, you understand it immediately. It’s a pretty straightforward equation, just kind of plug in the numbers. Sometimes they are asking you three times to do the same steps over and over and then yeah you just, plug it in, if you understand it once then you just do what the professor asks, plug in the numbers...
528	Interviewer:	Ok.
529	Malcolm:	....usually they don't ask, but sometimes he does.

Like Hoban, Malcolm says that although he tends not to use plug-n-chug techniques, sometimes the professor intends for students to use them.

Summary of Students’ Use of Plug-n-Chug Strategies

Though there is little evidence of students using plug-n-chug techniques to solve the interview problems, students discussed their use of these techniques more generally. Some students think that there are problems that the professors intends for them to solve using plug-n-chug techniques. Most students view these techniques as being inadequate for solving problems. Overall, the interview participants varied in their willingness to use plug-n-chug techniques. For example, Zoe tries not to plug-n-chug unless she is stuck on a problem or unfamiliar with the physical principles that are needed to solve the problem. In contrast, Hoban views these techniques as an efficient way to solve problems and he tries to use them whenever he can.

Qualitative Analysis Activities

The Ball Drop problem was a very easy problem for the students and an extensive qualitative analysis was not needed for them to solve this problem. However, two of the qualitative activities were observed: visualization and categorization. The more difficult Tarzan problem provided opportunities to observe the other qualitative activities.

Visualization

Visualization was mentioned as an important part of solving physics problems for many of the interview participants, and nearly all the students begin their solutions for both problems by drawing a picture (See Appendix 4).

Table 7-3 summarizes the evidence for visualization for both the Ball Drop and Tarzan Problems.

Table 7-3: Evidence of visualization in students' solutions of the Ball Drop and Tarzan Problems. Quotes from students are italicized.

Student	Ball Drop Problem	Tarzan Problem
Zoe	Draws a picture [Line 365]	*Ok. Let me draw a picture so...is he on a cliff? And does he have like an initial velocity at all or is he just like standing there? Ok. So we're on the edge...and he has a vine, and he swinging down like this, or is he...? Ok. Umm, can you explain to me again? On the way down?* [Lines 609-619]
Simon	Draws a picture [Line 4]	*I'm try...I'm trying to reason kinda through, in my head, trying to figure out whether if he was just holding onto the vine, and...like, in air, and it doesn't break, would swinging on it exert, like increase the force so that it would break?* [Line 196]
Jenny	*Ok, then I'm looking for the final velocity - and its not moving when I drop it right? OK now I'll draw a picture.* [Line 87]	*So there's my Tarzan on the vine and there's some maximum tension ... OK ...is ... at whatever height he starts from on the vine does he already have tension in the vine or is he starting it with slack and dropping onto it ... so that it like like like is he swinging like this or is he going like that?* [Line 277] ... *because you definitely have mg going down .... unless ... is he just like stepping off a ledge or is he like jumping out?* [Line 301]
Kaylee	*Umm, first I drew a diagram, 'cause I always do that. Just to visualize it. It's a lot easier if I can visualize it.* [Lines 8-14]	Starts by drawing a picture [Line 181]
Hoban	No picture	Draws a picture [Line 88]
Malcolm	Draws a picture [Line 247]	Draws a picture [Line 419]
Nathan	Draws a picture [Line 87]	Draws a picture [Line 301]

Several students made additional general statements related to visualization. For example, Zoe characterizes herself as a “visual person” four times during the interview [Lines 109, 165, 189, 367]. Jenny discusses how visualization is generally important in her ability to solve physics problems. “So if I can't picture the movement I'm gonna have problems which is why upper division scares me 'cause apparently you have to stop picturing movement or you can’t picture it or something” [Line 117]. Malcolm also talks generally about visualization. “You have to go all the way through the whole process. Sometimes I do picture it in my mind” [Line 377].

Additionally, Zoe, Simon, Jenny, and Malcolm commented on the pictures drawn in the sample solutions. Zoe discussed using the picture as evidence of the author’s understanding.

522	Interviewer:	Ok. So if you were going to give this student a grade on their work here what criteria would you use?
523	Zoe:	Umm. Usage of like proper equations...
524	Interviewer:	Ok.
525	Zoe:	...and they have a picture which is good because, for me I don't think just plugging and chugging for equations is like really understanding physics.

Simon, Jenny, and Malcolm referred back to the picture to help them interpret the sample solution.

170 Simon: Uh, from the picture, I can't really tell um, which way's positive, which ways negative, I guess. And like in m...the way I did it, I went off of uh, the total energy [starts writing on his solution again] and then I subtracted the potential energy so it's automatically negative, and in my mind I'm thinking that up is positive and down is negative and I know it's falling, so it would have a negative velocity. And it looks like they have a negative sign but I'm not sure if down is negative or up's negative.

267 Jenny: … it's also weird that they changed to "x" so they could say that this is zero. They should keep this "s" or they should say "x" is equal to "s minus s_0" which is kinda weird but I feel that they understand what is going on. They also didn't label anything in that picture which is kinda weird well 'cause this could be like a ball or it could be like this is zero or then I don't know what this little thing… oh this is a ball yeah, it looks like there is two pictures I'm kinda but I feel like the picture like its basically what's happening in the picture is really to help them so if you don't need a picture then…

455 Malcolm: Yea so I think this may be (mumble). Ok let's see so, so let's see so here he's saying umm, say we have a maximum tension that is allowed that's given...ok and and this force is umm, equal, is it going to be equal to this? Let's see, at the given instant...wait, what's this, so if we have speed going in to maintain the (mumble)...ok, ok so let me, I'm going to have to look back to this picture...(mumble).

The interview participants recognize visualization as being an important part of their problem solving process. All of the interview participants visualized the objects and interactions of the problem situations. This visualization happened early in the solution process, though some students did more visualization or revisited their drawings later in their solutions.

The interview participants drew diagrams as an external representation of their visualizations. Most of them drew diagrams for both interview problems, even for the easy Ball Drop problem, and some of the students drew several diagrams for the Tarzan Problem. Students also used the diagrams in the sample solution to aid in their interpretation of the solution. Some of the functions of these diagrams include providing information about what variables mean, acting as references for how quantities change, illustrating relevant aspects of the geometry of the problem, and representing specific system configurations.

Problem Categorization

Problem categorization is recognized as having an important role in problem solving. Studies involving algebra word problems and physics problems have shown that problem categorization happens quickly, and expert-novice comparisons suggest that categorization helps direct problem solving approaches [53, 79]. These interviews contain much evidence of students' categorizing the ball drop problem, and little evidence of students categorizing the Tarzan problem.

In solving the Ball Drop problem, the students either remembered a solution that they had done before or identified the problem as belonging to a known class of physics problems. Table 7-4 summarizes the evidence of categorization during the students' solutions of the ball drop problem.

Table 7-4: Evidence of categorization in students' solutions of the Ball Drop problem. Quotes from students are italicized.

Student	Evidence of Problem Categorization
Zoe	Interviewer: *So when you, when you first saw this problem was energy the first way you thought of to solve it?* Zoe: *Umm, not at first. I got confused because we were talking about the...what was it called...projectiles, and so I got confused, but then I realized I had uhh, potential-energy...*[Line 401].
Simon	*I knew that it was a kinematics problem* [Line 8] *Um, yeah I could [use energy conservation]. Um, I don't know, I think of using [that] more for ramp problems.* [Line 50]
Jenny	*This one I wouldn't really think too much about it 'cause I've done dropping problems so much* [Line 89]
Kaylee	Doesn't explicitly discuss categorization for either problem. She does discuss memories of having solved the Ball Drop Problem before, but her initial attempt to solve the problem is unsuccessful. Ball Drop Problem [Lines 8-24]
Hoban	Talks about the Ball Drop Problem as being a "projectile" problem and discusses memories of having solved this problem many times before [Line 12]
Malcolm	Talks about knowing from experience that an energy solution is faster than a kinematics solution. First he talks about it from what seem to be his own experiences solving this problem, then he also talks about grading his students' solutions solving this problem. *Ok, so I thought this way would avoid some math. One thing I know just from experience is that this way is faster and it's more fun using energy conservation.* [Line 285]. *I remember that this problem when I had it for the first time, I did it this way. So this [kinematics] could get complicated if you had more stuff happening here, this would get messy while this [energy] would remain pretty nice* [Lines 297-301].
Nathan	Talks extensively about his teaching experiences – he is very familiar with a kinematics solution because this is the solution path most commonly used by his students. He mentions that the kinematics equations were difficult to remember when he was a student, but teaching has helped him to remember them.

In contrast, no student mentioned remembering a known solution to the Tarzan problem (though several used analogies to understand parts of the problem, as will be discussed below). Hoban tries to think of a similar problem to Tarzan that he has done in the past but is unsuccessful. “Umm, no I don’t remember doing a problem like this. I probably did, though, but I'm not going to remember the results of that” [Line 100]. Again, like Zoe, Hoban attempts to remember similar problems in order to help him generate his solution.

More generally, Kaylee talks about using categorization as a way of thinking about physics ideas. “[When solving problems] I probably think of problems that I've done before...similar problems...that's kinda thinking about the physics ideas for me” [Lines 456-460].

Summary of Visualization and Problem Categorization

All of the interview participants were comfortable with visualization and categorization. Visualization was important both in generating solutions and in interpreting the solutions of others. Several students discuss visualization as being extremely helpful in solving problems. Categorization helped students identify a solution approach. Categorization may be related to students’ familiarity with the problem; there was more evidence of categorization for the familiar Ball Drop problem than in the more difficult, less familiar Tarzan problem.

Drawing Analogies to Familiar Situations

While solving the difficult Tarzan problem, several students discussed analogous situation as a way to make progress towards a solution. After Zoe was able to visualize the problem and clarified to herself what the problem was asking, she talked about two problems that she had done in the past. These problems were similar enough to the Tarzan problem that she found it helpful to consider them: a Ferris wheel problem and a car going over a hill problem.

623	Zoe:	Ok. Umm...well I guess I would assume that the tension at the bottom..no matter..umm, let's see, so say we drawn the man...there 'm' 'g' down....I know this has to do with the umm, kinda like a, merry-go-round, not a merry-go-round umm, what are they called… Ferris wheel problem...
624	Interviewer:	Ok.
625	Zoe:	Where I know at the top he's feeling really, really light, and at the bottom there is more normal force....
626	Interviewer:	Ok.
627	Zoe:	So, I dunno, like I always go confused on this part where since you feel light there is more normal force, being pushed up on you or is it little?
628	Interviewer:	Well what do you think?
629	Zoe:	Uhh, (mumble) umm, well, I remember, ok so basically since I'm not quite understanding this problem I'm relating it to other problems that we've done in class...so we have the first part is the ferris-wheel..
630	Interviewer:	Umm-kay.
631	Zoe:	...where in this point you're feeling really pushed down into the seat so...because you feel pushed down more there's more, well not more 'm' 'g' but, there's a lot more normal force, and when you're here there's prolly a little, and I know that because there's another problem we did, which was that, which also had to do with umm, circular problems and there's a car that's going at a

		certain velocity...
632	Interviewer:	Umm-hmm.
633	Zoe:	...and I remember that, we looked for the normal force at zero, which would be just enough for him, for the car, to not fly off in a certain direction.
634	Interviewer:	Ok.
635	Zoe:	So, I would assume that at the top, since you feel the same kind of feeling that the normal force would be zero or less here, and there would be more normal force here...
636	Interviewer:	Ok.
637	Zoe:	...which means that, I guess there's more normal force here, so that should be greater here, and if it relates to...umm, how fast he's going and he's going in a circular motion, I know it would relate to, umm centrifical, or centripical... "centrifical" or "centripical"?
638	Interviewer:	Centripetal.
639	Zoe:	Centripit-
640	Interviewer:	Yea, it's a tough one...
641	Zoe:	ok...so which equals 'v' squared over 'm' is that right or was it...'v' squared over 'r'! So that makes sense because he is going around in a circle, and if he were to go all the way up, just, let's just say, then he would feel really really light..and it's going in a circular motion so now after like that. And Newton's little diagram here. So, uhh, he would reach at gre... so if he started at a higher point, a higher cliff or whatever and he dropped more then that would give him more velocity right here, oops, and, and then there would be a greater acceleration, or a greater feeling...

Zoe uses the Ferris wheel problem to draw an analogy between the normal force that the Ferris wheel booth exerts on the passenger and the force that the vine exerts on Tarzan. She uses the car going over a hill problem to understand how speed will be related to the tension in the vine. In the end, she cannot formally relate tension to acceleration, but she uses these analogies to help her correctly conclude that the initial height will affect whether the vine breaks.

Simon also draws an analogy to a familiar situation to help him understand the Tarzan problem. The analogy he uses is making a turn in a car.

196	Simon:	I'm try...I'm trying to reason kinda through, in my head, trying to figure out whether if he was just holding onto the vine, and...like, in air, and it doesn't break, would swinging on it exert, like increase the force so that it would break?
197	Interviewer:	Ok
198	Simon:	I guess that's how, that's kinda how I'm thinking of it.
199	Interviewer:	And so, which do you think it is?
200	Simon:	For some reason, I want to say no.
201	Interviewer:	That the swinging doesn't increase the force?
202	Simon:	Right.
203	Interviewer:	Ok. But you're not sure why?
204	Simon:	But I'm not sure why. I [sighs] cause I kinda think about it, you know, like, rotational motion, or like say like a car turning, and you know, getting pushed out to the side, how like in the reference frame of like the car you feel like there's something pushing you out.
205	Interviewer:	uh-huh
206	Simon:	But, in this situation, I feel like for force, the mass times acceleration. And acceleration would be because of gravity which shouldn't change. So, to me it seems like just if he was holding it, and it does not break, swinging wouldn't break it either.

In Simon's case, his experiences are in conflict with his formal evaluation of the problem situation, causing him to be unsure about his analysis. His formal analysis leads him to conclude that the initial height shouldn't matter, but he remembers that it feels like there is an outward force acting on him when making a turn in the car, and he is not sure how to resolve these two ideas. This analogy causes Simon to doubt his formal analysis (which is, in fact, incorrect), but the analogy does not help him toward a correct solution.

Kaylee uses an analogy of a bucket of water moving in a vertical circle to confirm her formal analysis of the Tarzan problem. Kaylee had realized that her solution indicated that if Tarzan weighs more, the maximum height that he can start from will be greater.

256	Kaylee:	Because the force-centripetal is greater so it is, it's like the water in the bucket when you rotate it.
257	Interviewer:	What do you mean?
258	Kaylee:	Like if you turn a water, if you just turn a bucket of water upside down then the water's going to fall out but if it has a velocity if it has a centripetal force then it won't.
259	Interviewer:	Ok, and so what's the connection here? You were talking about like the weight and the centripetal force and then you started talking about the water, so I just wanna be able to follow your reasoning here.
260	Kaylee:	Yea. So this, the greater centripetal force would be helping the tension to counterbalance the force of gravity...
261	Interviewer:	Ok.
262	Kaylee:	...so...yea the greater the height the greater the force-centripetal is gonna be.
263	Interviewer:	Ok.
264	Kaylee:	Which helps the tension more, or it allows the tension, this ones going to be greater so the tension can be smaller and still have the same, not the same but...

Kaylee uses this analogy to confirm that the greater the speed of an object, the greater the centripetal force. This realization is followed by an incorrect understanding of the relationships of forces acting on Tarzan.

Like Kaylee, Malcolm tries to confirm his analysis of the Tarzan problem by making an analogy between Tarzan and a pendulum.

449	Malcolm:	Umm-hmm. I guess I should have mentioned another way of looking at it that would, I guess, support my argument would be that you have a pendulum, it's kind of taken for granted to derive the fact that the period is g/l, you can consider two examples that if you observe the Tarzan here, uhh, if you start it here but you observe him from here and on for example this point and observe a Tarzan starting at this point and umm, no actually it's wrong, never mind...

Malcolm was attempting to use the pendulum to support his analysis of the Tarzan problem that the initial height does not affect whether the vine breaks. Interestingly, he realized his pendulum analogy does not support his analysis of Tarzan, yet he disregarded the analogy without double checking his analysis.

During Jenny's discussion of the Ball Drop problem, she brought up an experience she had in her high school physics class that helped her to understand the physics of objects moving under the influence of gravity. Earlier in the interview she identified an object moving on a curved track as a problem that she'd rather use energy conservation than kinematics.

238	Interviewer:	OK so I want to go back to something that you said. You said that the acceleration of the ball on this circular track is gonna be the same as if it was in free fall?
239	Jenny:	If its frictionless and its not loosing anything to friction
240	Interviewer:	OK

241	Jenny:	Because I remember in high school we did this thing where we had like different inclined planes like at different angles but the heights were all the same which I drew badly umm, and the ball got like the thing basically got to the bottom at the same time and any difference you could account to friction you should avoid friction and it should be the same like to go down like this and versus the drop that way
242	Interviewer:	OK
243	Jenny:	So it shouldn't be any different for a curved track. I mean the instantaneous acceleration maybe different if I think about it, 'cause its going from a steeper to a... no … yea... sorry I'm confusing myself
244	Interviewer:	OK
245	Jenny:	so, because I ... I was thinking like well you should make it to the bottom at the same time... right and these two situations and in this one, so I'm thinking your acceleration would have to be... like like 'cause you are covering a different distance so your... umm .. so your acceleration would have to be umm different to get you there .. but on average you should... I've confused myself
246	Interviewer:	OK
247	Jenny:	I tend to get into these loops and the I have to stop and go back

In this case, Jenny makes a mistake in “remembering” that blocks start sliding down ramps of different inclinations with the same initial height will reach the bottom of the ramps at the same time (when in fact, they will reach the bottom with the same speed but at different times). During her discussion, she realizes a contradiction in her analysis (that steeper inclination means greater instantaneous acceleration). She does not resolve this conflict during the interview. The analogy she is trying to use is between a curved track (changing slope) and several tracks of different, constant slopes. In this case, Jenny is trying to use an analogy of her personal experience with the inclined plane experiment to justify her statement of equal accelerations.

Summary and Discussion of Students' Uses of Analogies

Many interview participants were comfortable using analogies. While characterization was more common for the familiar Ball Drop problem, analogies were discussed more often for the Tarzan problem. Students used analogies to make progress towards a solution and for justifying an answer at the end of the solution. Experimental evidence was used to make an analogy in support a general statement about acceleration. Other analogies involved familiar situations from previously solved problems.

For the analogies made in these interviews, there was a moderate amount of surface similarity between the target problem and the previously solved problem. Almost all of the analogies used in Tarzan had to do with objects moving in a vertical circular trajectory (in contrast, Simon talked about a car turning a corner). Jenny's analogy had to do with surfaces that had components parallel and perpendicular to the ground. The students used these analogies to understand and model the interactions in the target problem by drawing parallels to the successful analyses of the previously solved problems. These data suggest that in order to identify a solution approach, sometimes students identify a previously solved problem with surface features similar to those of the target problem, then modify the previously successful analysis or result and apply it to the target problem. This model of analogy-use works better for the case of using an analogy to generate a solution than for using an analogy to support a solution. In the case of supporting a solution, a different model of analogy-use might be that the analysis of the target problem is done first and then used to identify problems that were solved using a similar analysis. Then the similarity of a previously solved problem (i.e. surface features) could be used to confirm the analysis of the target problem. Further investigation is needed to describe the role of surface features in making analogies.

Dimensional Analysis

Dimensional analysis is when a problem solver considers the mathematical relationships between different types of physical quantities (i.e. length, mass, time, etc). Dimensional analyses are commonly done as a check to see if an error was made in a computation. This type of dimensional analysis is also referred to as a process of “checking units”. Dimensional analysis can also be used to generate a solution [78] by considering the dimensions of the desired end-product and the physical quantities that are thought to be important. Generative dimensional analyses do not guarantee a correct answer (dimensionless quantities are usually not included), but are a convenient way to make a quick approximation.

Several of the interview participants mentioned dimensional analysis during the interviews. Jenny talked about using dimensional analysis to make sense out of equations and for checking her answers.

100	Interviewer:	OK, so let’s talk about this solution then. This first equation that you wrote down, does that equation make sense to you?
101	Jenny:	On the basic sense, yes.
102	Interviewer:	So what do you mean by "on the basic sense"?
103	Jenny:	I mean it makes sense that you would have the... you would have some initial velocity and that if you take your ... if you add an

		acceleration and ... times a distance to it that you would get some new velocity
104	Interviewer:	So why does the multiplication of this acceleration and the distance and then you add that onto the speed makes sense?
105	Jenny:	'cause the acceleration is meters per second squared, right?
106	Interviewer:	OK
107	Jenny:	…and the you are multiplying it by meters so you have meters squared per second squared ... so... and the velocity is meters per second which you are squaring so you also have meters squared per second squared and if you add things that don't have the same units then you mess up your units.
108	Interviewer:	OK
109	Jenny:	I think of it... its sort of like a like, when you have like, like two meters per second it's like writing 2x so you can't add that to 4y if y was like meters per second squared.
110	Interviewer:	OK so...
111	Jenny:	So you have to make your units agree.

451	Interviewer:	OK, do you do a lot of like figuring out the dimensions to make sense out of equations?
452	Jenny:	Oh, like how it would be in one dimension versus two dimensions?
453	Interviewer:	No, not that. I mean more like, umm, the units on the variables
454	Jenny:	Oh, umm sometimes. I am learning to do that more. I never used to really look at units except at the end to make sure I had the right units on my answer, but I've found that umm it's good to use your units.

Malcolm also mentions using dimensional analysis as a way of checking answers and sometimes for sense-making.

564	Interviewer:	Do you ever do like dimensional analysis to make sense out of formulas?
565	Student:	Ok, umm to make sense out of them? Yea I'm sure it's a good way to I never did it, I did dimensional analysis to see if my solution was correct to a problem.

566	Interviewer:	So it's more of a like checking your answer type of thing for you?
567	Student:	Yea, dimensional analysis, umm, but yea if it's something simple like energy or momentum yea then that's, that would be pretty good to do dimensional analysis.
568	Interviewer:	Ummkay.
569	Student:	Yea, but if it's something pretty messy then I guess it's nice to do since, if you have a lot of constants also sometimes if you do the dimensional analysis you can actually get those constants and they are in the correct form because sometimes some e over some kind of constant gives you the same units as if it was squared over the square root of the other one but sometimes the dimensional analysis will give you exactly the relationship between those different constants and then you can check your answer at the end...
570	Interviewer:	Yea.
571	Student:	...so it's more than just dimension check.

Hoban also discussed using dimensional analysis to make sense out of an equation while elaborating on his CLASS responses.

238	Interviewer:	OK Umm.. Number 13 it says "I do not expect physics equations to help my understanding of the ideas, they are just for doing calculations" Do you agree, disagree, why or why not?
239	Hoban:	Umm, well I think a lot of times you can get some insight from the equation
240	Interviewer:	Like what kinds of insight?
241	Hoban:	I mean, well, a lot of times looking at the units of the equations will tell you what its talking about sometimes.

Hoban was observed to use a generative dimensional analysis while solving the Tarzan problem.

106	Hoban:	Yea, well that's how I started, drawing all the forces, and came up with the only forces are just from the gravity at the very bottom anyway.
107	Interviewer:	What do you mean?

108	Hoban:	Well I guess when he is swinging through you might have… well it’s not really a force... but the velocity would be like this and there would be some downward velocity plus the gravity but I guess that would not contribute cause ... that should not contribute to the tension I have to look up the units for the tension I guess
109	Interviewer:	Tension has units of force
110	Hoban:	That’s what I thought so the velocity shouldn’t contribute cause ... pause... right? ... I don’t care about this part anyway, I only care about the bottom ... ‘cause that’s where the tension would be the max anyway right?
111	Interviewer:	So you are thinking that the tension is changing as its swinging down?
112	Hoban:	Yea, but that shouldn’t happen either should it? (undecipherable muttering) that way… yes, it should be the same the whole way through, and I guess it will get a piece from velocity and a piece from gravity.
113	Interviewer:	I guess I am confused as to how velocity contributes on a force diagram.
114	Hoban:	Yes, that’s what I'm confused on too.
115	Interviewer:	OK
116	Hoban:	‘cause I'm working on the units but the units don’t make sense.
117	Interviewer:	OK, so you are trying to do some kinda dimensional analysis type thing now?
118	Hoban:	Yea, to see if it should be in there which it doesn’t seem like it should be because I can't multiply it by anything reasonable to get force out of it.
119	Interviewer:	So along with this force stuff you have this acceleration… is that an acceleration?
120	Hoban:	Uh huh, well that’s...
121	Interviewer:	So what is that over there?
122	Hoban:	I was just checking like the ... it should be like the tangential acceleration, I think that is what that equation is. No that’s radial isn’t it? It is ... I can’t remember. No, I think that is radial. It should be radial. So this... oh OK... it should be equal to that.
123	Interviewer:	The acceleration is equal to what?
124	Hoban:	Umm, this should be equal to the tension. This is the radial acceleration which I think that’s what it was... cause the angle would be L times theta dot or something... its just theta ... I need to look it up.

125	Interviewer:	Sure.
126	Hoban:	I'm working too hard thinking about things (looks at reference, finds what he wants pretty fast, writes and mutters, looks at ref again, really trying hard, writing)... yes it does matter on the height I guess it, as long as it's moving in a circle and then what happens if like h is different from r ... that should be fine ... (mutters)... yes this should get me the tension ... (mutters... pause)...why did m come back?
127	Interviewer:	Why are you worried about m?
128	Hoban:	To get the units to work out right
129	Interviewer:	Oh, OK

Hoban has serious conceptual difficulties with centripetal acceleration and applying Newton's 2nd law (he equates the tension in the vine with the centripetal force but does not include Tarzan's weight in the analysis), but using a generative dimensional analysis helps him to make some progress towards a solution.

These excerpts show that students use dimensional analysis for three purposes. The most comfortable use (at least for the interview students) is to check answers for an algebraic mistake. Students also use dimensional analysis to make sense out of equations, though this seems to be more difficult for the students. Hoban demonstrated an ability to use dimensional analysis to generate a solution.

Making Simplifying Assumptions

In order to make difficult problems more tractable, expert problem solvers make assumptions that render calculations easier to perform or reduce the complexity of the problem by limiting the physical principles that need to be considered to successfully solve the problem. There were two occasions during the interviews where the issue of making a simplifying assumption was discussed. The first occurred while Jenny was trying to use the concept of work to solve the Ball Drop problem. She attempted to integrate the acceleration of the ball over time in order to relate force to speed.

177	Jenny:	Well I could say “a squared over 2” but the integral thing is really saying that some function “a” in terms of time or some other variable is gonna be “v” in terms of that same variable so I don’t think that works .. 'cause this is talking about a function not a of t equals a [a(t)=a] which I guess it could be, but you can’t assume that.
178	Interviewer:	For the case of the ball dropping you can’t assume that?
179	Jenny:	I wouldn’t think you could ever assume that because I tend to make wrong assumptions a lot so I try not to.

In this case, Jenny talks about being uncomfortable making assumptions that would make a calculation easier. She could assume that the acceleration is constant in time which would make the integral easy to evaluate, but she lacks the confidence to do so, and she is left with an integral that she doesn’t know how to evaluate.

Malcolm makes a simplifying assumption in his discussion of the Tarzan problem.

418	Interviewer:	And so the question that I would like for you to think about is: How high up can Tarzan start swinging so that the vine doesn't break at the bottom of the swing. Like what is the maximum height that he can start from so that the vine doesn't break at the bottom of the swing?
419	Malcolm:	Ok, so lets discuss I think it's not good to, if he starts at more than 90 degrees since I know (mumble) just start falling down and (mumble) on the rope right so?

The simplifying assumption that Malcolm makes here is putting a constraint on the possible answers. In this case, the first thing he does when starting to consider the Tarzan problem is to put an upper bound on Tarzan’s maximum height. This constraint allowed him to forego consideration of how the vine would react to a sudden increase in tension. Here, Malcolm is able to make an explicit assumption that narrows the amount of physics that needs to be considered.

Considering Limiting Cases

Another expert-like problem solving activity is considering limiting cases. Typically this is done by finding a solution and then checking what happens to the solution in the case that one of the physical quantities gets very large or very small . These cases are useful because they can often be compared to problem solvers' intuition easily.

During the interviews, two students demonstrated an ability to consider limiting cases [57]. Both of these instances occurred while the students solved the Tarzan problem. In both cases, the students used a limiting case analysis to respond to a follow-up question posed by the interviewer: what happens to the maximum height if Tarzan is heavier? Neither student spontaneously did a limiting case analogy to check their solutions; the analysis was done in response to the follow-up question.

251	Interviewer:	So what would happen in this problem if Tarzan were heavier, would that affect the height?
252	Kaylee:	Ok, so he's heavier then that'll be bigger so then this term will be smaller...it's negative that doesn't work.

253	Interviewer:	What do you mean? So what are you thinking about?
254	Kaylee:	If he's heavier then this'll be greater so then this term will be smaller...so then the height in general will be greater, that doesn't seem right. Because if he's heavier there should be a greater force and it should break sooner. 'r'...that looks right, yea that seems right.
255	Interviewer:	Ok.
256	Kaylee:	Because the force-centripetal is greater so it is, it's like the water in the bucket when you rotate it.
257	Interviewer:	What do you mean?
258	Kaylee:	Like if you turn a water, if you just turn a bucket of water upside down then the water's going to fall out but if it has a velocity if it has a centripetal force then it won't.
259	Interviewer:	Ok, and so what's the connection here? You were talking about like the weight and the centripetal force and then you started talking about the water, so I just wanna be able to follow your reasoning here.
260	Kaylee:	Yeah. So this, the greater centripetal force would be helping the tension to counterbalance the force of gravity...
261	Interviewer:	Ok.
262	Kaylee:	...so...yea the greater the height the greater the force-centripetal is gonna be.
263	Interviewer:	Ok.
264	Kaylee:	Which helps the tension more, or it allows the tension, this ones going to be greater so the tension can be smaller and still have the same, not the same but.

388	Interviewer:	OK, and in your mind is the centripetal force the same as the tension in the rope or is it ..
389	Nathan:	It is a component of the tension in the rope

390	Interviewer:	The centripetal force is a component of the tension in the rope
391	Nathan:	Right
392	Interviewer:	OK
393	Nathan:	Yea, I see the tension in the rope as having two components there is a component that is causing centripetal motion and then there is a component that is overcoming Tarzan's gravitational force downwards
394	Interviewer:	OK, so if Tarzan was heavier would that change the height that he would have to start at?
395	Nathan:	Yea, because that component ... because there is a net tension budget of that (points to sheet of paper) so if you decrease so if you eat up more of that by a bigger mass then you have less of it to spend on the centripetal force, so you have less of it to spend on the velocity thus less of it to spend on the height.
396	Interviewer:	So, I'm trying to figure out what you said. So you are saying that if Tarzan is heavier right? that is changes the initial height that he can start at
397	Nathan:	Right
398	Interviewer:	Because there is more gravitational ... the gravitational force is bigger ... is a bigger component of the tension
399	Nathan:	Right
400	Interviewer:	And so the centripetal force is gonna be a smaller fraction? or is the same amount?
401	Nathan:	Err, well the centripetal force has to be a smaller fraction of the total tension if its not gonna break
402	Interviewer:	OK
403	Nathan:	Because I'm thinking of everything in context of breaking the vine

When Kaylee considers the limiting case of Tarzan being really heavy, she has to go through the analysis twice. At first, she incorrectly concludes that increasing Tarzan's weight causes the initial height to be negative (an incorrect assessment of her solution). Then, she goes back and corrects herself. However, her second analysis is incomplete. She does not recognize that her solution indicates that if Tarzan is very heavy, or if the breaking tension goes to zero, the height does not go to zero. Although Kaylee's attempts a limiting case analysis, she lacks proficiency with it.

Nathan, however, performs a correct limiting case analysis. He describes the tension as having two pieces – one balances Tarzan's weight and the other causes the centripetal acceleration. He correctly explains that if Tarzan's weight increases, then there is less force to cause a centripetal acceleration.

Summary of Simplifying Assumptions and Limiting Cases

Few students considered limiting cases or made simplifying assumptions while solving the interview problems, and some of the students who did attempt these activities were uncomfortable or lacked proficiency. The extent to which students do either of these activities spontaneously in their own problem solving is unknown (i.e. frequency, circumstances). The interview participants' apparent discomfort with these activities suggests that the students do not regularly consider limiting cases or explicitly make simplifying assumptions while solving problems.

Conclusions

These interviews demonstrate that undergraduate physics majors use both qualitative analysis heuristics and plug-n-chug techniques in their problem solving. Though few observations were made of students using plug-n-chug techniques, most students discussed them more generally in their problem solving. Most students admitted to using plug-n-chug strategies, though most recognized this as a problem solving technique that does not lead to or involve deep understanding. Plug-n-chug strategies were largely viewed as a survival strategy, used when the relevant material is unfamiliar, when stuck, or when the professor intends for the problem to be solved in this way.

Some qualitative analysis activities are more commonly used by physics majors than others. All of the interview participants were comfortable with using visualization and categorization, and most identified visualization as a highly-valued skill in solving physics problems. Most students were comfortable with drawing analogies in two circumstances: in generating a solution and in trying to support a solution. While categorization was more important for the familiar Ball Drop problem, drawing analogies was more important for the unfamiliar Tarzan problem. Many of the students said they are comfortable with using a dimensional analysis to check their solutions. A few of the students also said they were becoming more comfortable with using dimensional analysis to make sense out of equations, and one demonstrated an ability to use a generative dimensional analysis, though this seems much less common.

Few students displayed comfort and proficiency with making simplifying assumptions or considering limiting cases. Both of these heuristics can require the coordination of multiple modes of thinking: mathematical skills (like proportional reasoning or evaluating the complexity of certain computations), conceptual knowledge (like the conditions in which some assumptions can be made) and real world experiences (like knowing how interactions would proceed in extreme cases). Both of these heuristics require a nominal amount of confidence that inexperienced students may lack.

Chapter 8: Conclusion

This thesis follows a tradition of exploring student knowledge, abilities, and views by comparing them to experts and novices. Survey results and interviews provide evidence that undergraduate physics majors have many useful views and abilities that can be built upon to help these students increase their expertise in physics.

Physics majors arrive at the university with relatively expert-like views about the nature of physics knowledge, ways to study physics, and solving physics problems. These views are even more expert-like at the senior year of undergraduate study and the first year of graduate study. Interviews with students revealed that undergraduates and experts share similar views about what kinds of problem solving activities lead to deep understanding, but their circumstances as students encourages more time-efficient ways of studying and solving problems (like plug-n-chug techniques).

Physics majors' personal interest in physics was found to be uniformly high, and views about sense-making activities appear more expert-like with increased experience. Students are also seen to report their views in stronger terms towards the end of undergraduate study, which may indicate that generally these beliefs become more codified with experience. Interviews revealed that some upper level students consider themselves to be physicists, coinciding with a stage when undergraduate surveys scores become highly expert-like.

Views about conceptual understanding seemed to be affected by the transition between sophomore-level and junior-level coursework, and these survey results are supported by discussions from the interviews. While talking about Lagrangian mechanics, students characterized these techniques as being mathematically complex and revealed that these techniques have little conceptual meaning to them. From a cognitive standpoint, this lack of semantic meaning is problematic for storing and retrieving information from long term memory. Only one of the four interview participants who had taken courses in this material was able to give even an overview of a solution using a Lagrangian approach, though he could not carry out the details to complete the solution. If current research in upper level courses reveals this trend to be widespread, physics departments should have serious discussions about the goals of these courses and teaching techniques that could be used to improve student conceptual understanding. One department that has already done so is Oregon State University. Their approach has been to radically redesign their junior and senior level courses into what they call the "Paradigms Program" [80]. Though little has been reported about changes in learning outcomes, student and faculty feedback has been quite positive.

These interviews provide evidence that students' knowledge organization is influenced by the content sequence of their courses. Students were likely to suggest a kinematics solution approach over their preferred energy approach for the Ball Drop problem. They said they choose this approach because kinematics was the first approach they learned. Restructuring the content sequence of physics courses may help students organize their knowledge in a more expert-like way. Several curricula that have been informed by PER have non-traditional content sequences [81], though their effect on knowledge organization has not been studied.

The interviews suggest that students do not choose solution approaches by considering multiple options and selecting their preferred approach. Rather, students proceed with the first approach they think of until they get stuck and need to switch. It was also observed that some students develop a kind of tunnel vision once a solution is found. Identifying a successful solution seems to make finding other solutions more difficult.

When faced with an unfamiliar problem, physics professors have been observed to approach the problem by looking for conserved quantities. The interview participants did not do this during the interviews. However, like physics professors, the students were able to use analogies to understand and make progress on an unfamiliar problem. Looking for conserved quantities is a highly generalized solution approach, while the student's analogies had a moderate amount of surface similarity to the target problem. The analogies were also often connected to real world experiences. The interview participants were able to use remembered solutions to the more familiar Ball Drop Problem. These results show that while experts are known to use solution techniques that have been generalized from many problem solving experiences, physics majors seem to rely on analogies influenced by real world experiences and adapting solutions from archetypal problems for problem solving.

It is hoped that by identifying the views and practices of intermediate level students, teaching strategies can be designed to help students achieve a deeper understanding of physics ideas and superior analytical skills. Improving the education of students who pursue careers in physics will influence their graduate study experiences and may potentially impact future research in physics. Studies like this provide additional data that can be used to develop and refine theories of how cognitive transformations occur (i.e. theories of transfer [82]). Ultimately, by furthering the community's understanding of how physics majors think, this study will help direct reform efforts that work toward helping students learn physics and helping teachers teach more effectively.

Appendix I: Description of Courses Surveyed

Descriptions of UCSD physics courses surveyed (from UCSD General Catalog 2005/2006).

4A. Physics for Physics Majors–Mechanics: The first quarter of a five-quarter calculus-based physics sequence for physics majors and students with a serious interest in physics. The topics covered are vectors, particle kinematics and dynamics, work and energy, conservation of energy, conservation of momentum, collisions, rotational kinematics and dynamics, equilibrium of rigid bodies.

4B. Physics for Physics Majors–Mechanics, Fluids, Waves, and Heat: Continuation of Physics 4A covering oscillations, gravity, fluid statics and dynamics, waves in elastic media, sound waves, heat and the first law of thermodynamics, kinetic theory of gases, second law of thermodynamics, gaseous mixtures and chemical reactions.

4C. Physics for Physics Majors–Electricity and Magnetism: Continuation of Physics 4B covering charge and Coulomb's law, electric field, Gauss's law, electric potential, capacitors and dielectrics, current and resistance, magnetic field, Ampere's law, Faraday's law, inductance, magnetic properties of matter, LRC circuits, Maxwell's equations.

4D. Physics for Physics Majors–Electromagnetic Waves, Optics, and Special Relativity: Continuation of Physics 4C covering electromagnetic waves and the nature of light, cavities and wave guides, electromagnetic radiation, reflection and refraction with applications to geometrical optics, interference, diffraction, holography, special relativity.

4E. Physics for Physics Majors–Quantum Physics: Continuation of Physics 4D covering experimental basis of quantum mechanics: Schrödinger equation and simple applications; spin; structure of atoms and molecules; selected topics from solid state, nuclear, and elementary particle physics.

100A. Electromagnetism: Coulomb's law, electric fields, electrostatics; conductors and dielectrics; steady currents, elements of circuit theory. Four hours lecture.

100B. Electromagnetism: Magnetic fields and magnetostatics, magnetic materials, induction, AC circuits, displacement currents; development of Maxwell's equations. Four hours lecture.

100C. Electromagnetism: Electromagnetic waves, radiation theory; application to optics; motion of charged particles in electromagnetic fields; relation of electromagnetism to relativistic concepts. Four hours lecture.

110A. Mechanics: Coordinate transformations, review of Newtonian mechanics, linear oscillations, gravitation, calculus of variations, Hamilton's principle, Lagrangian dynamics, Hamilton's equations, central force motion. Four hours lecture.

110B. Mechanics: Non-inertial reference systems, dynamics of rigid bodies, coupled oscillators, special relativity, continuous systems.

130A. Quantum Physics: Phenomena which led to the development of quantum mechanics. Wave mechanics; the Schrödinger equation, interpretation of the wave function, the uncertainty principle, piece-wise constant potentials, simple harmonic oscillator, central field and the hydrogen atom. Observables and measurements. Four hours lecture.

130B. Quantum Physics: Matrix mechanics, angular momentum and spin, Stern-Gerlach experiments, dynamics of two-state systems, approximation methods, the complete hydrogen spectrum, identical particles. Four hours lecture.

130C. Quantum Physics: Scattering theory, symmetry and conservation laws, systems of interacting particles, interaction of electromagnetic radiation with matter, Fermi golden rule, and the relativistic electron.

140B. Statistical and Thermal Physics: Applications of the theory of ideal quantum gases in condensed matter physics, nuclear physics and astrophysics; advanced thermodynamics, the third law, chemical equilibrium, low temperature physics; kinetic theory and transport in non-equilibrium systems; introduction to critical phenomena including mean field theory.

161. Black Holes and The Milky Way Galaxy: The structure and content of the Milky Way galaxy and the physics of black holes. Topics will be selected from: general relativity, theory and observation of black holes, galactic x-ray sources, galactic structure, physical processes in the interstellar medium, star formation. Physics 160, 161, and 162 may be taken as a three-quarter sequence for students interested in pursuing graduate study in astrophysics or individually as topics of interest.

Appendix II: Details of Games-Howell Analysis of CLASS Categories

Difference in Average % Favorable for each CLASS category, with Post-Hoc Test Results (an * indicates statistical significance at the 0.05 level)

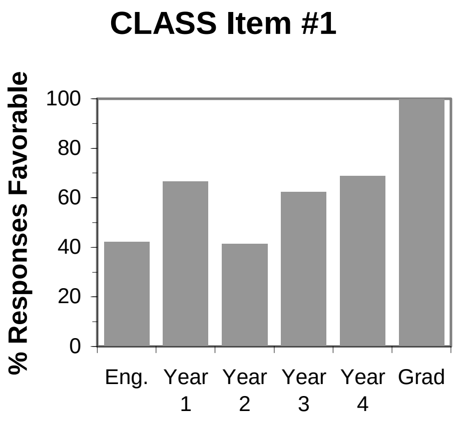
Category	Group i	Group j	Difference in Average % Favorable (i-j)	P
Personal Interest	Eng	Year 1	-1.91*	<.001
		Year 2	-2.34*	<.001
		Year 3	-1.62*	<.001
		Year 4	-2.35*	<.001
		Grads	-1.89*	.022
	Year 1	Year 2	-0.43	.698
		Year 3	0.29	.946
		Year 4	-0.43	.682
		Grads	0.02	<.001
	Year 2	Year 3	0.72	.063
		Year 4	0	<.001
		Grads	0.45	.890
	Year 3	Year 4	-0.72	.057
		Grads	-0.27	.989
	Year 4	Grads	0.46	0.885
Real World Connections	Eng	Year 1	-.90*	<.001
		Year 2	-1.09*	<.001
		Year 3	-.62*	.002
		Year 4	-1.19*	<.001
		Grads	-0.61	.687
	Year 1	Year 2	-0.19	.959
	Year 1	Year 2	-0.19	.959
		Year 3	0.28	.822
		Year 4	-0.29	.827
		Grads	0.29	.981

	Year 2	Year 3	0.47	.222
		Year 4	-0.09	.998
		Grads	0.49	.856
	Year 3	Year 4	-0.56	.107
		Grads	0.02	1.000
	Year 4	Grads	0.58	.759
Sense Making & Effort	Eng	Year 1	-.94*	.020
		Year 2	-1.19*	.003
		Year 3	-1.24*	<.001
		Year 4	-1.91*	<.001
		Grads	-2.70*	<.001
	Year 1	Year 2	-0.25	.985
		Year 3	-0.3	.932
		Year 4	-.97*	.036
		Grads	-1.77*	<.001
	Year 2	Year 3	-0.05	1.000
		Year 4	-0.72	.257
		Grads	-1.51*	<.001
	Year 3	Year 4	-0.67	.092
		Grads	-1.46*	<.001
	Year 4	Grads	-0.79*	.021
Conceptual Connections	Eng	Year 1	-1.22*	.001
		Year 2	-.99*	.007
		Year 3	-.97*	<.001
		Year 4	-1.94*	<.001
		Grads	-2.63*	<.001
	Year 1	Year 2	0.22	.989
		Year 3	0.24	.972
		Year 4	-0.72	.291
		Grads	-1.42*	.002
	Year 2	Year 3	0.02	<.001
		Year 4	-0.94	0.070

		Grads	-1.64*	<.001
	Year 3	Year 4	-.96*	.019
		Grads	-1.66*	<.001
	Year 4	Grads	-0.70	.234
Applied Conceptual Understanding	Eng	Year 1	-1.66*	.001
		Year 2	-1.07*	.021
		Year 3	-1.01*	.002
		Year 4	-2.39*	<.001
		Grads	-3.92*	<.001
	Year 1	Year 2	0.59	.805
		Year 3	0.65	.662
		Year 4	-0.73	.701
		Grads	-2.26*	<.001
	Year 2	Year 3	0.06	1.000
		Year 4	-1.33	0.074
		Grads	-2.85*	<.001
	Year 3	Year 4	-1.38*	.032
		Grads	-2.91*	<.001
	Year 4	Grads	-1.53*	.012
Problem Solving General	Eng	Year 1	-1.87*	<.001
		Year 2	-1.82*	<.001
		Year 3	-1.26*	<.001
		Year 4	-2.32*	<.001
		Grads	-2.51*	<.001
	Year 1	Year 2	0.05	1.000
		Year 3	0.61	.584
		Year 4	-0.45	.853
		Grads	-0.64	.498
	Year 2	Year 3	0.56	.699
		Year 4	-0.5	.802
		Grads	-0.69	.442
	Year 3	Year 4	-1.06	.054

		Grads	-1.25*	.009
	Year 4	Grads	-0.19	.993
Problem Solving Confidence	Eng	Year 1	-.98*	<.001
		Year 2	-.77*	.005
		Year 3	-0.27	.696
		Year 4	-.95*	.004
		Grads	-.91*	.003
	Year 1	Year 2	0.21	.947
		Year 3	.71*	.027
		Year 4	0.02	1.000
		Grads	0.07	.999
	Year 2	Year 3	0.5	.364
		Year 4	-0.19	.984
		Grads	-0.14	.989
	Year 3	Year 4	-0.69	.136
		Grads	-0.64	.072
	Year 4	Grads	0.04	1.000
Problem Solving Sophistication	Eng	Year 1	-1.87*	<.001
		Year 2	-1.46*	.001
		Year 3	-.96*	.005
		Year 4	-2.10*	<.001
		Grads	-3.17*	<.001
	Year 1	Year 2	0.41	.929
		Year 3	0.92	.186
		Year 4	-0.23	.995
		Grads	-1.30*	.014
	Year 2	Year 3	0.5	.777
		Year 4	-0.64	.690
		Grads	-1.71*	.001
	Year 3	Year 4	-1.14	.068
		Grads	-2.21*	<.001
	Year 4	Grads	-1.07	.087

Appendix III: Histograms of Responses to Individual CLASS Items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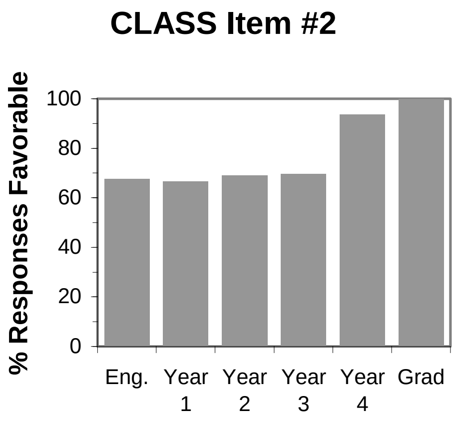
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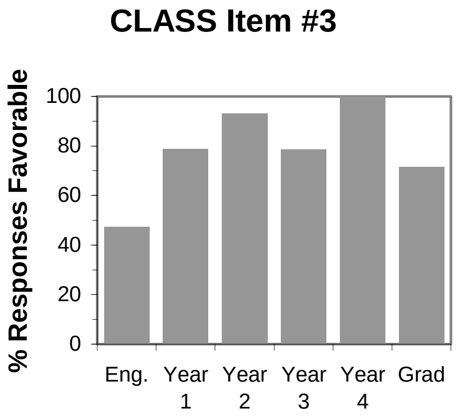
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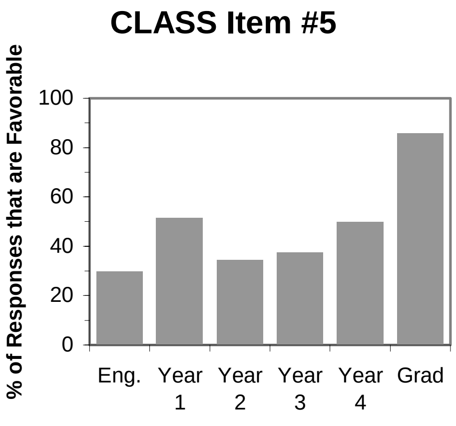
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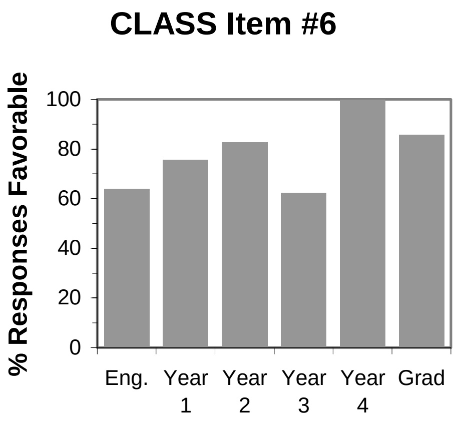
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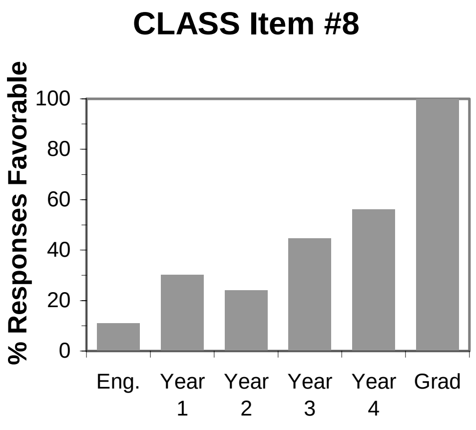
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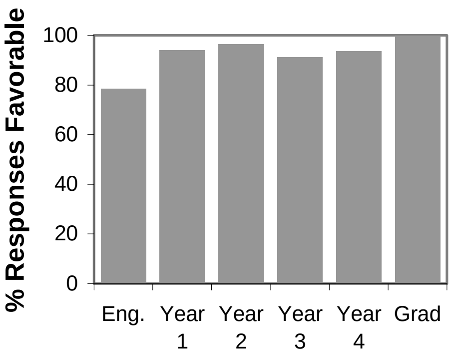
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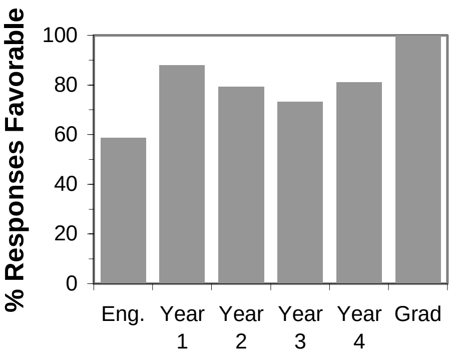
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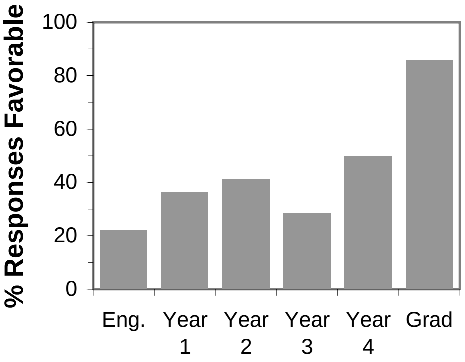
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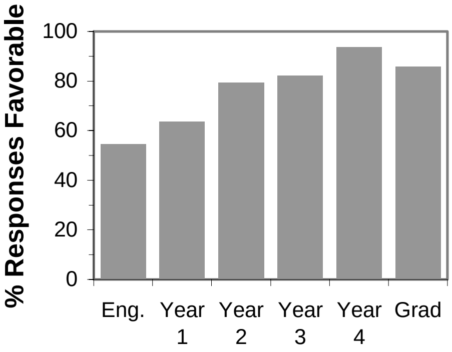
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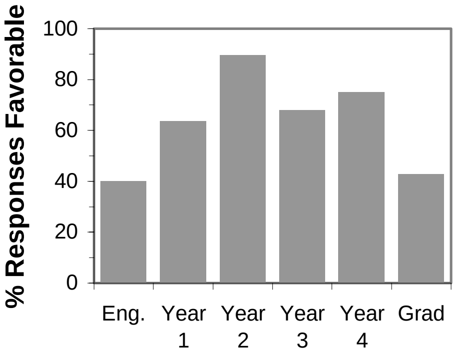
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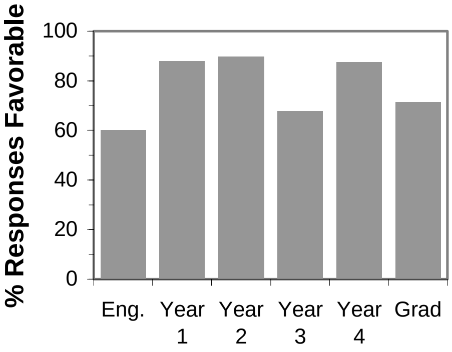
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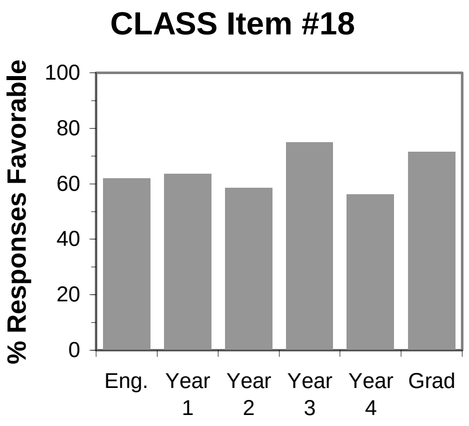
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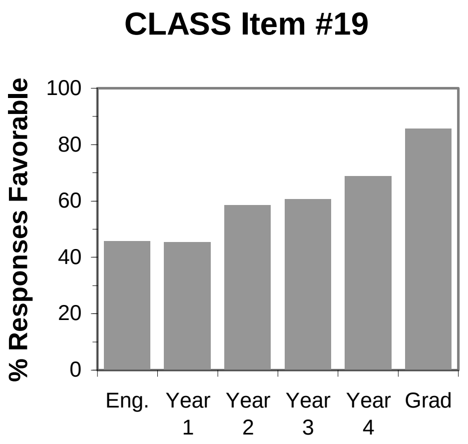
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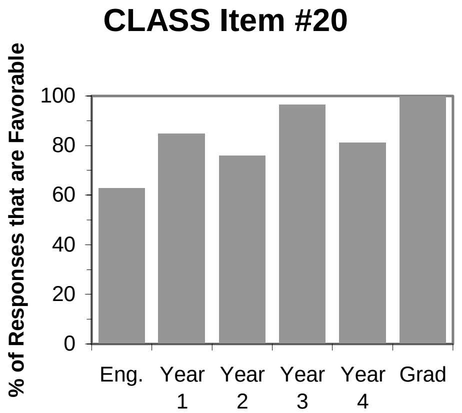
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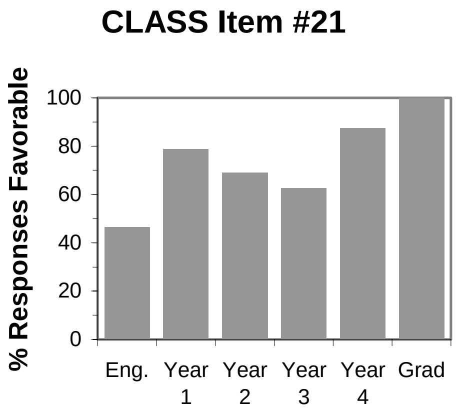
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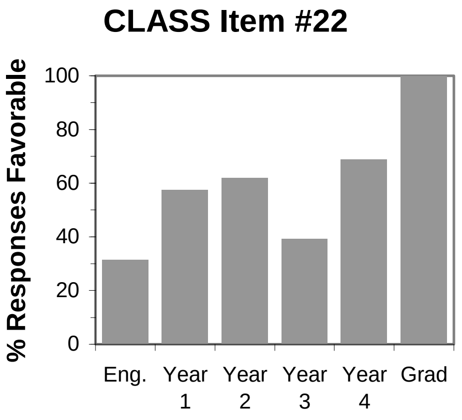
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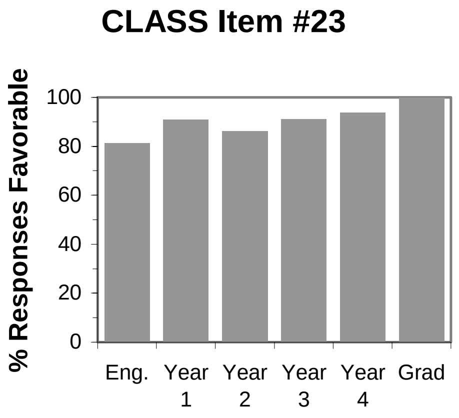
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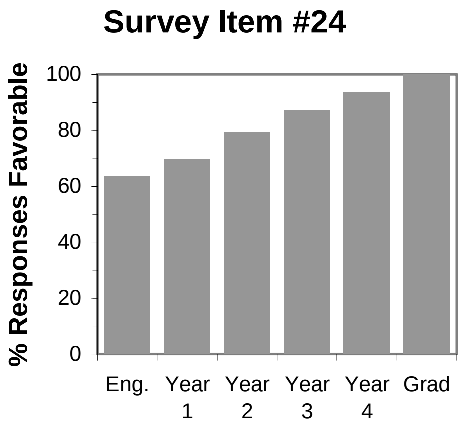
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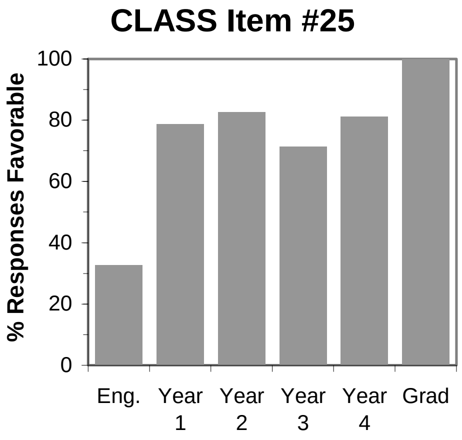
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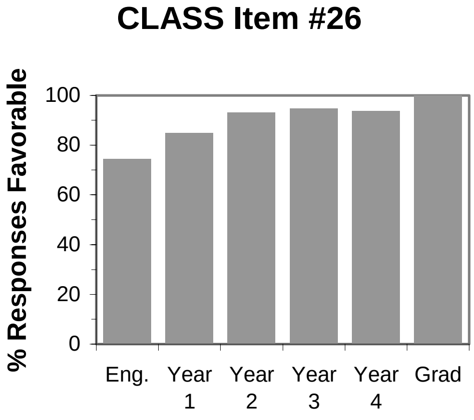
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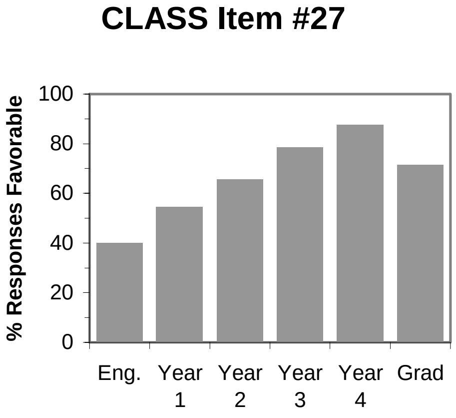
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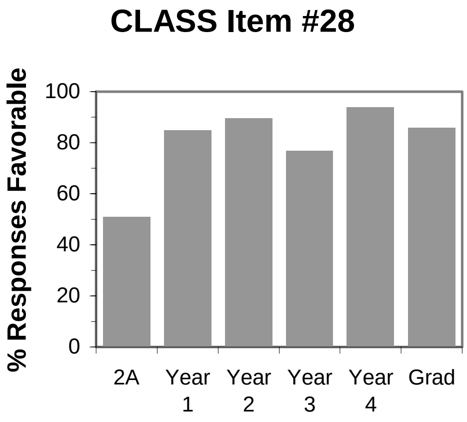
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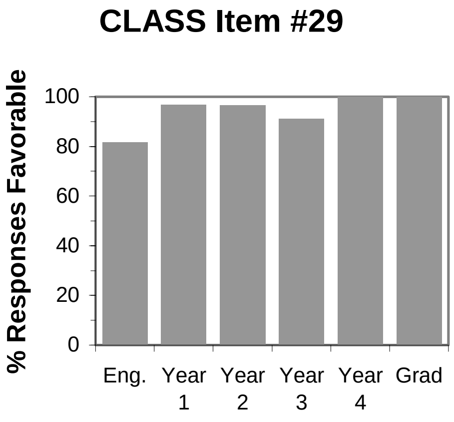
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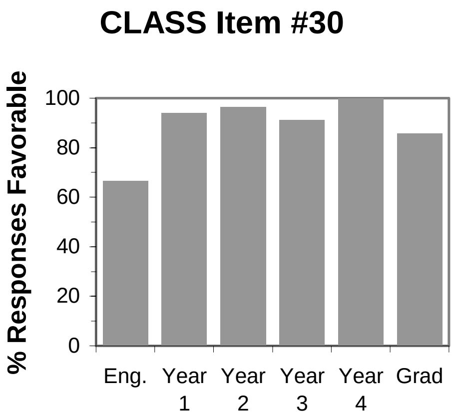
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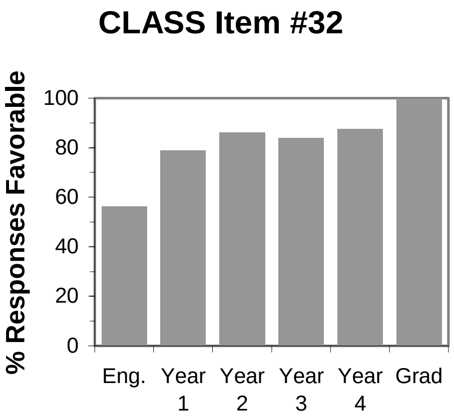
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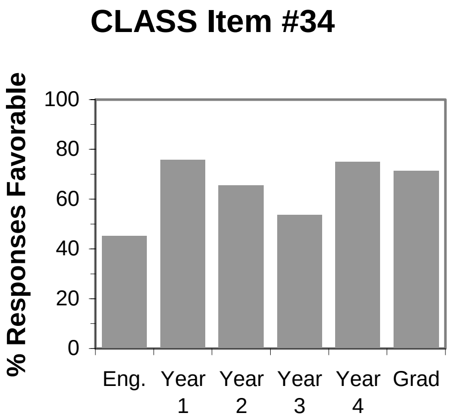
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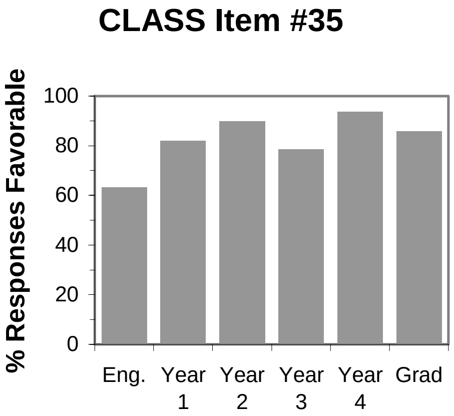
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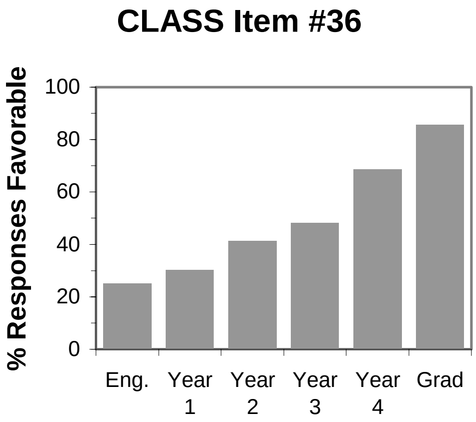
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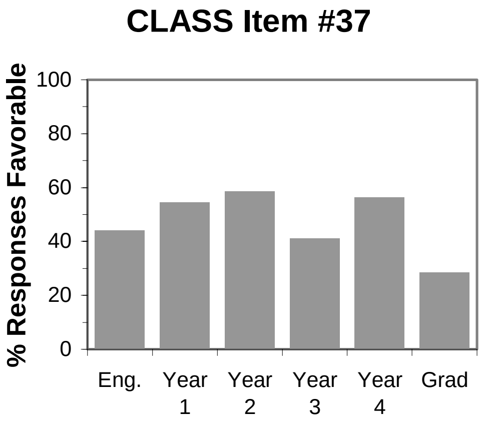
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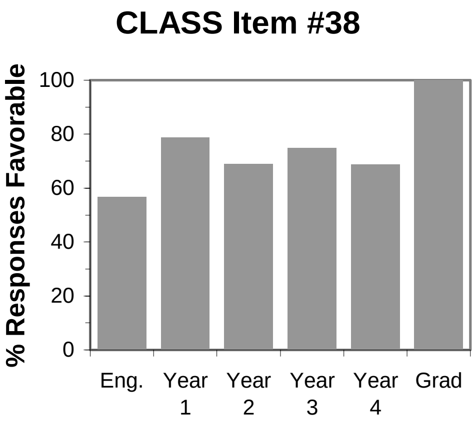
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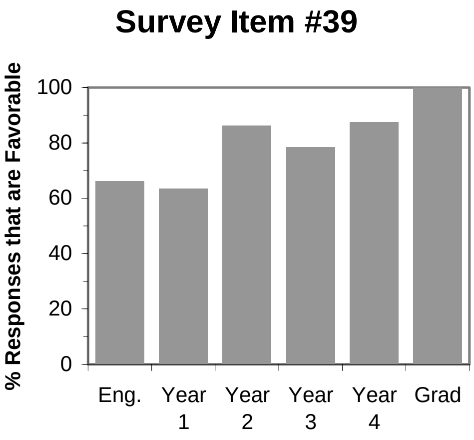
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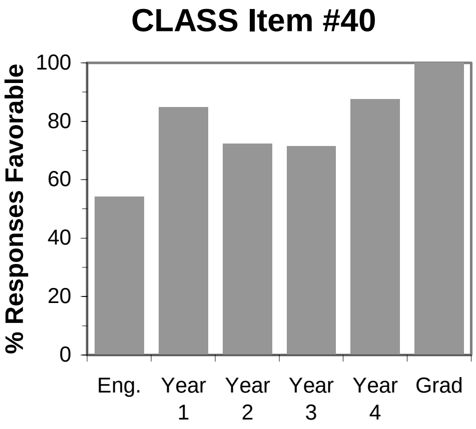
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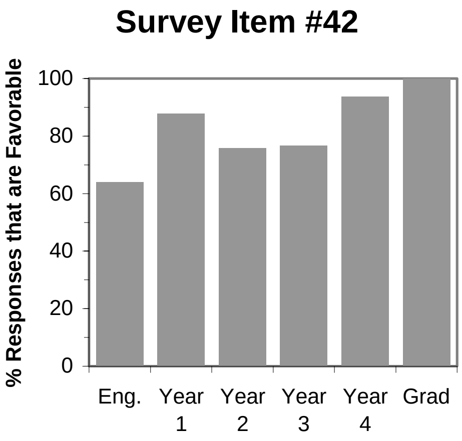
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Appendix IV: Example Solutions to Interview Problems

<u>Ball Drop Problem</u>: A ball with a known mass is dropped from a known height. What is the ball's speed right before it hits the ground?

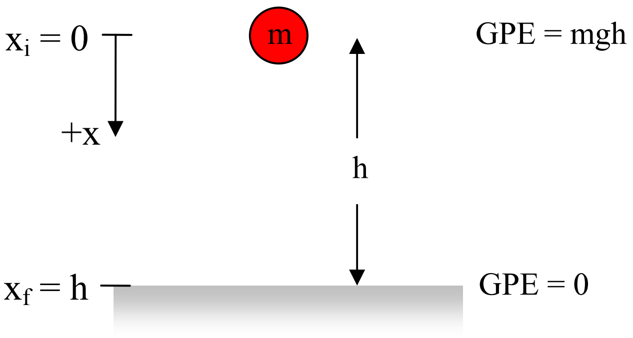


Figure 12.1: Illustration of Ball Drop Problem scenario, including quantities that are given in the problem statement and definition of a coordinate system used in solutions.

Known Quantities:

$$x_f - x_0 = h$$

$$a_x = g$$

$$v_0 = 0$$

<u>Solution 1: Kinematics (Time-Dependent)</u>

Start with the definition of acceleration and integrate twice to derive a general expression for the position of an object in free fall (constant acceleration):

$$a = \frac{dv}{dt} = g$$

$$v(t) = \int_0^t g\,dt'$$

$$v(t) = gt + v_0 \tag{12.1}$$

$$x(t) = \int_0^t v(t')dt' = \int_0^t (gt' + v_0)dt'$$

$$x(t) = x_0 + v_0 t + \tfrac{1}{2} g t^2 \tag{12.2}$$

To solve, solve Eq. (8.2) for time and evaluate Eq. (8.1) at the time when the ball hits the ground, t_f.

$$t = \sqrt{\frac{2h}{g}} \tag{12.3}$$

$$v_f = g\sqrt{\frac{2h}{g}}$$

$$\boxed{v_f = \sqrt{2gh}}$$

Solution 2: Kinematics (Time-Independent)

Solve for general time-independent kinematical equation by combing Eq. (12.2) and Eq. (12.3).

$$\frac{v_f - v_0}{g} = t$$

$$x_f = x_0 + v_0\left(\frac{v_f - v_0}{g}\right) + \tfrac{1}{2}g\left(\frac{v_f - v_0}{g}\right)^2$$

$$v_f^2 = v_i^2 + 2a(x_f - x_0) \qquad (12.4)$$

Plug in known values:

$$v_f^2 = 2gh$$

$$\boxed{v_f = \sqrt{2gh}}$$

Solution 3: Energy Conservation

Start with algebraic statement that mechanical energy is conserved (neglecting the dissipative effect of air resistance).

$$\Delta KE + \Delta GPE = 0$$

$$KE_f - KE_i + GPE_f - GPE_i = 0$$

$$\frac{1}{2}m\left(v_f^2 - v_0^2\right) - mg(x_f - x_0) = 0$$

$$\frac{1}{2}mv_f^2 = mgh$$

$$\boxed{v_f = \sqrt{2gh}}$$

Solution 4: Work-Energy Theorem

Start with the Work-Energy Theorem:

$$W = \Delta KE$$

$$\int_0^h \vec{F} \cdot d\vec{x} = \frac{1}{2} m\left(v_f^2 - v_0^2\right)$$

$$\int_0^h mgdx = \frac{1}{2} m v_f^2$$

$$mgh = \frac{1}{2} m v_f^2$$

$$\boxed{v_f = \sqrt{2gh}}$$

Solution 5: Impulse-Momentum Theorem

Start with the Impulse-Momentum Theorem:

$$\int_0^t \vec{F} dt' = \Delta \vec{p}$$

where p is the momentum of the ball.

$$\int_0^t mgdt' = m\Delta v$$

$$mgt = m(v_f - v_0)$$

Combine with Eq. (8.3):

$$mg\sqrt{\frac{2h}{g}} = m v_f$$

$$\boxed{v_f = \sqrt{2gh}}$$

Solution 6: Lagrangian Techniques

Start with defining the Lagrangian.

$$L = T - V = \frac{1}{2}m\dot{x}^2 + mgx$$

Use the Euler-Lagrange equations to find an equation of motion.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) - \frac{\partial L}{\partial x} = 0$$

$$m\ddot{x} - mg = 0$$

$$\ddot{x} = g$$

Integrate once to get the velocity as a function of time.

$$\dot{x} = \int_0^t g\,dt' = gt + v_0 \tag{12.5}$$

Integrate again to find the position as a function of time, and solve for the time it takes for the ball to hit the ground.

$$x(t) = \int_0^t \dot{x}\,dt' = \int_0^t \left(gt' + v_0\right)dt'$$

$$x(t) = \frac{1}{2}gt^2 + v_0 t + x_0$$

$$h = \frac{1}{2}gt^2$$

$$t = \sqrt{\frac{2h}{g}}$$

Plug into Eq. 12.5 to find the speed:

$$\boxed{\dot{x} = g\sqrt{\frac{2h}{g}} = \sqrt{2gh}}$$

<u>Tarzan Problem</u>: Tarzan is swinging on a vine that can withstand a known maximum amount of tension before the vine will break. Does Tarzan's initial height affect whether or not the vine breaks? If yes, what is the maximum height Tarzan can start swinging from before the vine breaks?

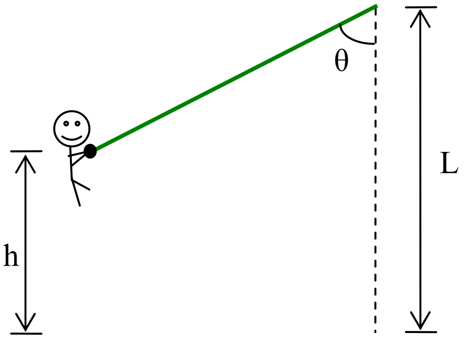
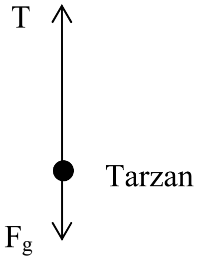


Figure 12.2

Solution 1: Newton's Laws and Energy Conservation

I'm going to relate the tension in the vine to Tarzan's initial height by looking by analyzing the forces acting on Tarzan and relating the forces to speed through centripetal acceleration. The maximum amount of force along the vine will occur at when Tarzan is at the bottom of the swing. The forces acting on Tarzan at the bottom of the swing are gravity and the tension in the vine. The tension in the vine is bigger than Tarzan's weight because he is accelerating towards the center of his circular trajectory.



Applying Newton's 2nd Law:

$$\sum F_{onTarzan} = ma_{centripetal}$$

$$T - F_g = \frac{mv^2}{L}$$

Use Energy Conservation to solve for Tarzan's speed at the bottom of the swing. Let Tarzan's initial height be measured relative to the bottom of the swing.

$$\Delta GPE + \Delta KE = 0$$

$$-mgh + \frac{1}{2}mv^2 = 0$$

$$v^2 = 2gh$$

Combining Newton's 2nd Law with Energy Conservation:

$$T_{\max} - F_g = \frac{m_{Tarzan}(2gh_{\max})}{L}$$

Tarzan's initial height does affect whether or not the vine will break. Now solve for the initial height.

$$\boxed{\frac{L}{2}\left(\frac{T_{\max}}{mg} - 1\right) = h_{\max}}$$

If the tension equals the maximum tension before the vine will break, then the above express will yield Tarzan's maximum initial height between 0 and L.

Solution 2: Lagrangian Mechanics

First, I need to define the Lagrangian using generalized coordinates. Since L represents the length of the vine, I'll use Λ to represent the Lagrangian.

$$\Lambda = \frac{1}{2}m\left(L\dot{\theta}\right)^2 + \frac{1}{2}m\dot{L}^2 - mgL\left(1 - \cos\theta\right)$$

Use the Euler-Lagrange equations to solve for the equations of motion. Solve for the radial direction first.

$$\frac{d}{dt}\left(\frac{\partial \Lambda}{\partial \dot{L}}\right) - \frac{\partial \Lambda}{\partial L} = 0$$

$$m\ddot{L} - mL\dot{\theta}^2 - mg\cos\theta = 0$$

The radial force will be largest when $\theta = 0$ (at the bottom of the swing). At the bottom of the swing:

$$m\ddot{L} - mL\dot{\theta}^2 - mg = 0 \tag{12.6}$$

Now, I need to find the angular speed when Tarzan is at the bottom of the swing.

$$\frac{d}{dt}\left(\frac{\partial \Lambda}{\partial \dot{\theta}}\right) - \frac{\partial \Lambda}{\partial \theta} = 0$$

$$mL^2\ddot{\theta} - mgL\sin\theta = 0$$

$$\ddot{\theta} - \frac{g}{L}\sin\theta = 0$$

This second order differential equation is difficult to solve analytically. What I need is to relate the tangential speed at the bottom to height at the top, so I'll use the concept of work.

$$W = \int \vec{F}_{net} \cdot d\vec{s}$$

In the tangential direction:

$$F_{net} = mg\sin\theta$$

Again, using Newton's 2nd Law:

$$-\int \left(mg\sin\theta\right) L d\theta = \int \left(mL\ddot{\theta}\right) L d\theta \tag{12.7}$$

The right side of Eq. 12.7 develops as follows (a quick-and-dirty derivation of the Work-Energy Theorem):

$$\int mL^2\left(\frac{d\dot{\theta}}{dt}\right) d\theta = \int mL^2 d\dot{\theta}\left(\frac{d\theta}{dt}\right)$$

$$= mL^2 \int_0^{\dot{\theta}_{bottom}} \dot{\theta} d\dot{\theta}$$

$$= \frac{1}{2} mL^2 \dot{\theta}_{bottom}^2$$

The left side of Eq. 12.7 develops as:

$$-mgL \int_{\theta_{\max}}^{0} \sin\theta d\theta = mgL\left(1 - \cos\theta_{\max}\right)$$

So, relating tangential speed with initial height:

$$mL\dot{\theta}_{bottom}^2 = 2mg\left(1 - \cos\theta_{\max}\right)$$

Combining with Eq. 12.6:

$$m\ddot{L} - 2mg\left(1 - \cos\theta_{\max}\right) - mg = 0$$

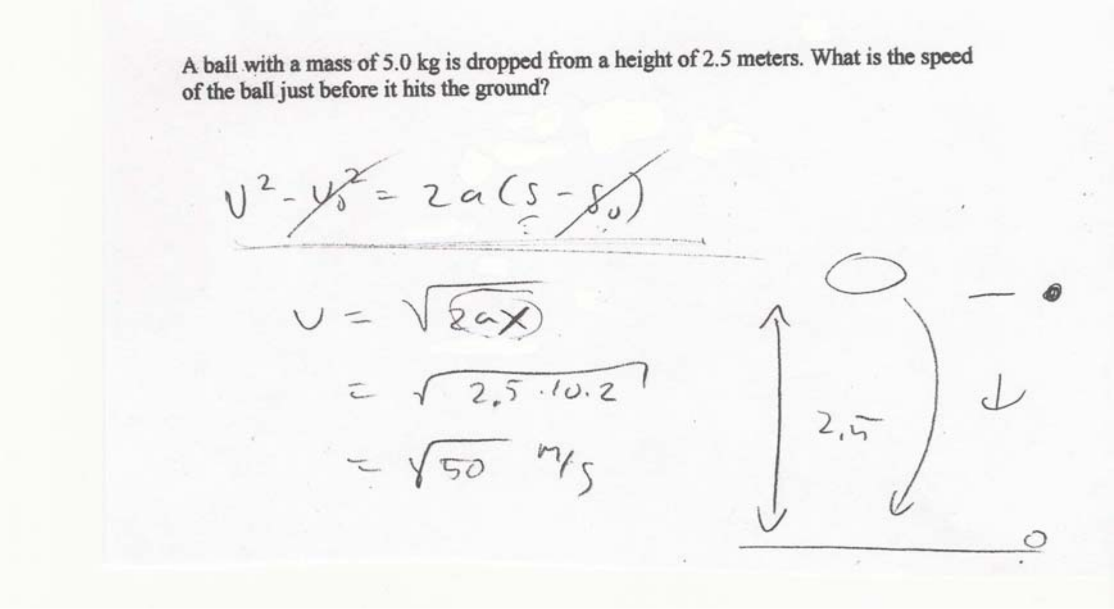
The maximum initial height is related to the maximum initial angle by $L\left(1 - \cos\theta_{\max}\right)$, so the result is:

$$\left(1 - \cos\theta_{\max}\right) = \frac{1}{2}\left(\frac{m\ddot{L}}{mg} - 1\right)$$

$$\boxed{h_{\max} = L\left(1 - \cos\theta_{\max}\right) = \frac{L}{2}\left(\frac{T_{\max}}{mg} - 1\right)}$$

Appendix V: Sample Solutions Given to Students

Ball Drop Solution



A ball with a mass of 5.0 kg is dropped from a height of 2.5 meters. What is the speed of the ball just before it hits the ground?

$$v^2 - \cancel{v_0^2} = 2a(s - \cancel{s_0})$$

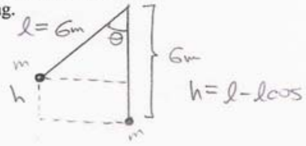
$$v = \sqrt{2ax}$$

$$= \sqrt{2{,}5 \cdot 10 \cdot 2}$$

$$= \sqrt{50} \ \mathrm{m/s}$$

Tarzan Solution

1. **Tarzan swings on a vine with a length of 6 meters. The vine can experience a tension of 1568 N before breaking. If Tarzan weighs 784 N (80 kg), what is the maximum initial height that he could start from without breaking the vine? Measure this height from the lowest point on the swing.**



$F_{max} = 1568N$

$F_g = 784N = mg$

$F_{max} - F_g = 1568N - 784N = 784N$

so, maximum $ma_c = 784N$

$ma_c = 784N$

$\frac{mv^2}{r} = 784N$

$v^2 = \frac{(784N)\,r}{m}$

$v = \sqrt{\frac{(784N)(6m)}{80kg}} = 7.67m/s$

TARZAN $\Sigma F = ma_c$

$-mg + T = ma_c$

system: tarzan and vine

before: $E = U_{grav} = mgh$

after: $E = K = \frac{1}{2}mv^2$

$-mg + T = \frac{mv^2}{r}$

$\sqrt{\frac{r(-mg+T)}{m}} = v$

$\sqrt{\frac{(6m)(-784N + 1568N)}{80kg}} = v = 7.67m/$

$mgh = \frac{1}{2}mv^2$

$gh = \frac{1}{2}v^2$

$h = \frac{v^2}{2g} = \frac{(7.67m/s)^2}{2(9.8m/s^2)} = \boxed{3m}$

check:

$\Sigma F = F_g + F_T = ma_c$

$F_T = ma_c + mg$

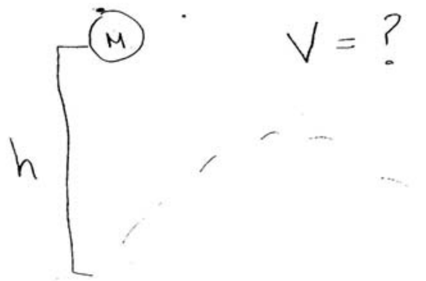
$F_T = \frac{mv^2}{r} + mg$

$F_T = \frac{(80kg)(7.67m/s)^2}{6m} + (80kg)(9.8m/s^2) = 1568N$

Appendix VI: Students' Written Work Generated in the Interviews

Solutions to the Ball Drop Problem:

Zoe



$V = ?$

$\Delta KE = \Delta U$

$\cancel{m}gh = \frac{1}{2}\cancel{m}v^2$

$\cancel{gh = v^2}$

$\cancel{\sqrt{\frac{gh}{2}} = v}$

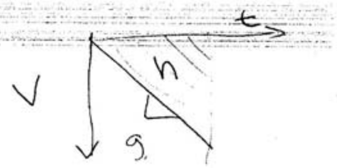
$\sqrt{2gh} = v$

h=10 $\sqrt{2(10)(10m)} = v$

$\sqrt{200} = v_1$

h=20 $\sqrt{2(10)(20m)} = v$

$\sqrt{400} = v_2$

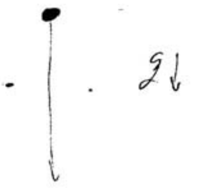


$h = \frac{1}{2} v \cdot t$

$\frac{v}{t} = a$

Simon

①



$v^2 = v_0^2 + 2a(y - y_0)$

$v^2 = 2a(y - y_0)$

$v = \sqrt{2a(y - y_0)}$

$TOT = KE + PE = 0$

$PE = KE$

$\cancel{m}gh = \frac{1}{2}\cancel{m}v^2$

$\sqrt{2g(h)} = v$

$\sqrt{2} \cdot \sqrt{g}\sqrt{h}$

$\overset{1.4}{2}\sqrt{gh} = v$

$2 \cdot \sqrt{g} \cdot \sqrt{h}$

$\boxed{\frac{G M_E m_2}{r^2}}$

$W = F \cdot d$

$= mgd$

$W = \Delta KE$

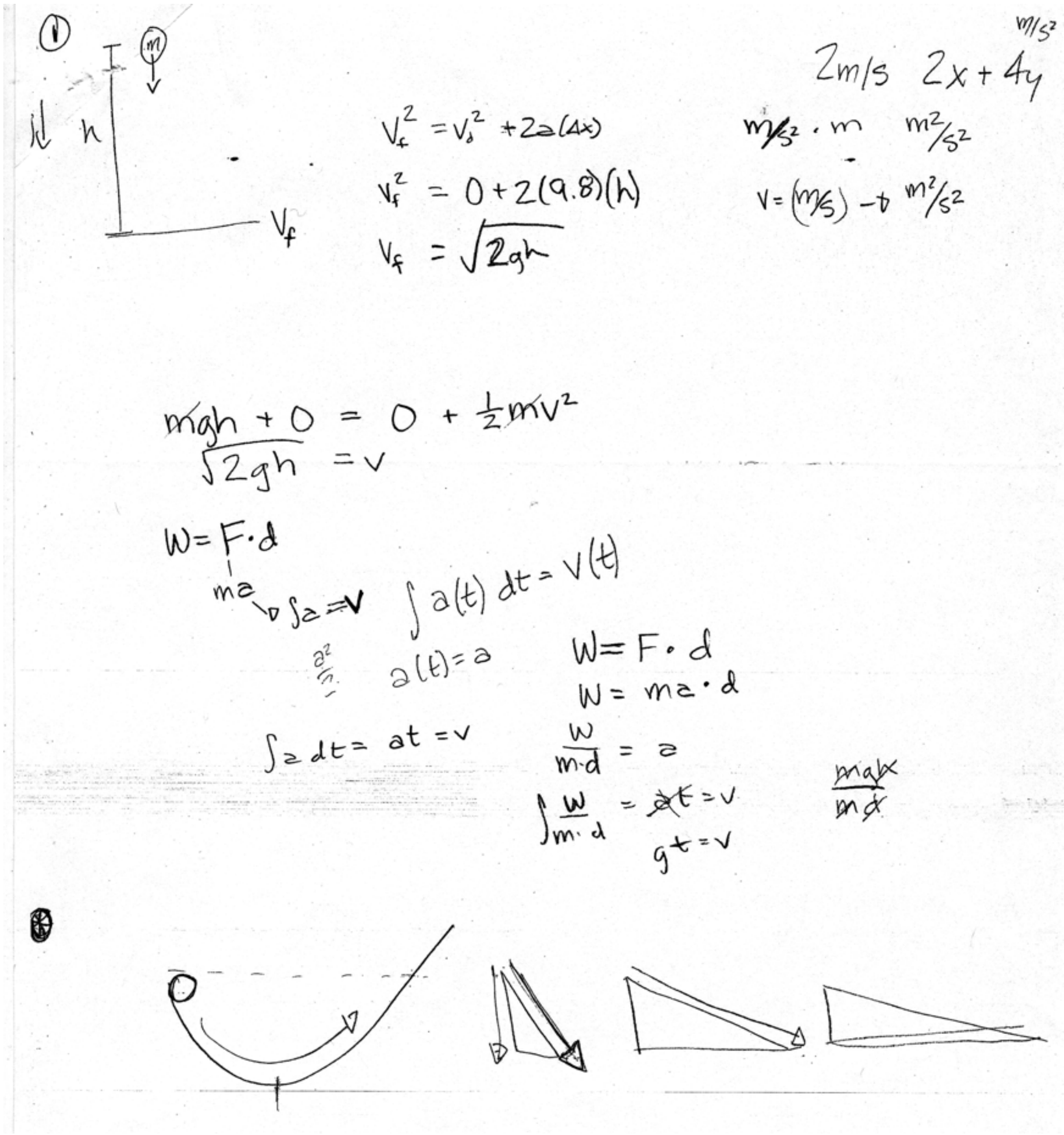
$W_{gravity} = \frac{1}{2}m(v_f - v_i)^2$

$\cancel{m}gd = \frac{1}{2}\cancel{m}(v_f - v_i)^2$

$2gd = v_f^2$

$\sqrt{2gd} = v_f$

<u>Jenny</u>



①

$2m/s \quad 2x + 4y$

m/s^2

$V_f^2 = V_0^2 + 2a(\Delta x)$

$V_f^2 = 0 + 2(9.8)(h)$

$V_f = \sqrt{2gh}$

$\cancel{m}/s^2 \cdot m \quad m^2/s^2$

$v = (m/s) \to m^2/s^2$

$\cancel{m}gh + 0 = 0 + \frac{1}{2}\cancel{m}v^2$

$\sqrt{2gh} = v$

$W = F \cdot d$

$ma \to \int a = v \quad \int a(t)\, dt = v(t)$

$a(t) = a$

$\int a\, dt = at = v$

$W = F \cdot d$

$W = ma \cdot d$

$\frac{W}{m \cdot d} = a$

$\int \frac{W}{m \cdot d} = \cancel{a}t = v$

$gt = v$

$\frac{\cancel{m}a\cancel{x}}{\cancel{m}\cancel{d}}$

Kaylee

$a = g$

$F = mg$

$v = at = gt$

$\cancel{m}gh = \frac{1}{2}\cancel{m}v^2$

$\sqrt{2gh} = V$

$mgh + \cancel{\frac{1}{2}mv_0^2} = \cancel{mgh_f} + \frac{1}{2}mv_f^2$

$\frac{1}{2}mv^2$

mv

Hoban

$\cancel{x = x_0 + \dot{x} + \frac{1}{2}\ddot{x}}$

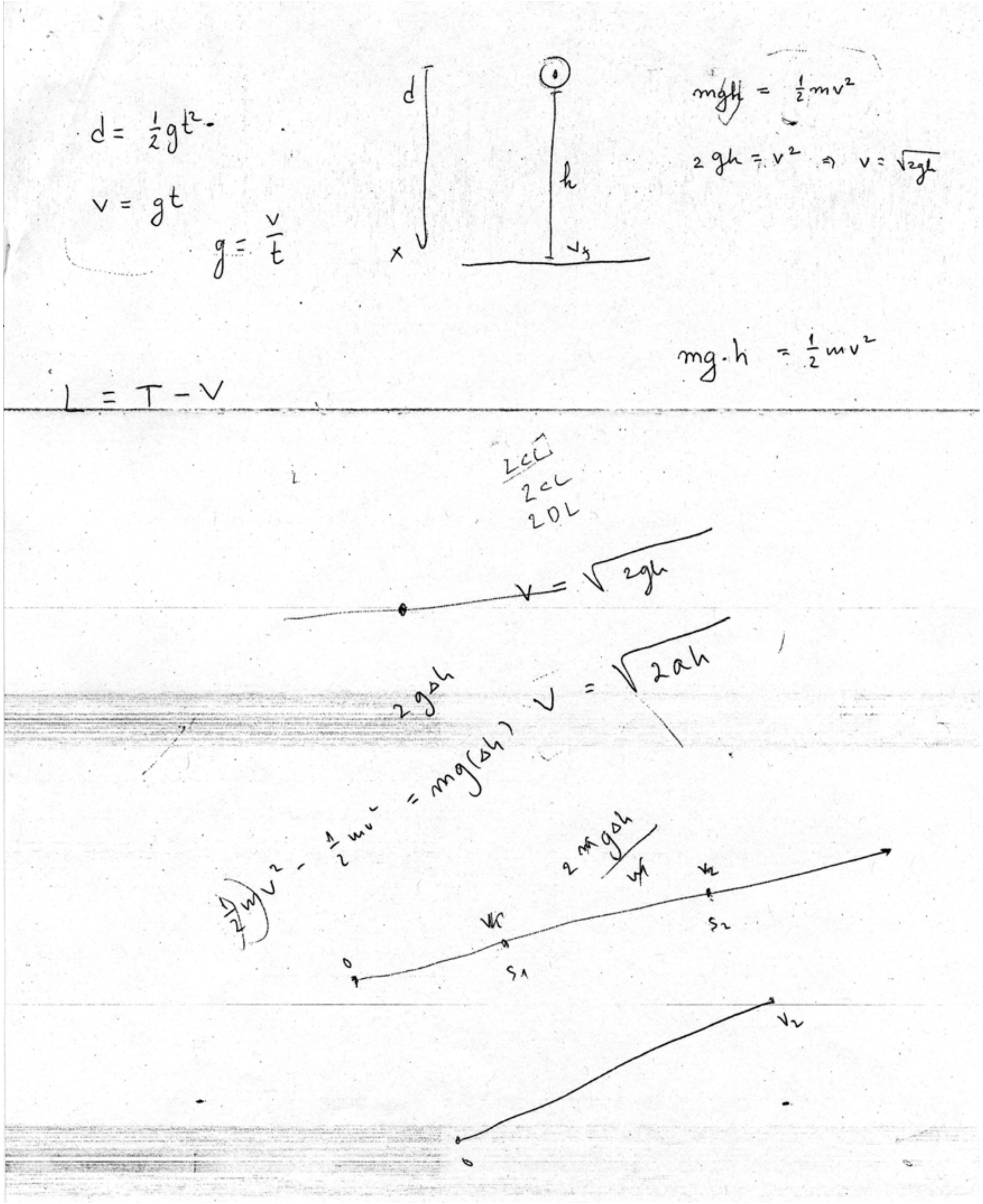
$mgh = \frac{1}{2}mv^2$

$gh = \frac{1}{2}\cancel{m}v^2$

$v^2 = 2gh$

$V = \sqrt{2gh}$

Malcolm



$d = \frac{1}{2}gt^2$

$v = gt$

$g = \frac{v}{t}$

$m g \cancel{H} = \frac{1}{2}mv^2$

$2gh = v^2 \Rightarrow v = \sqrt{2gh}$

$mg \cdot h = \frac{1}{2}mv^2$

$L = T - V$

2cC
2cL
2DL

$v = \sqrt{2gh}$

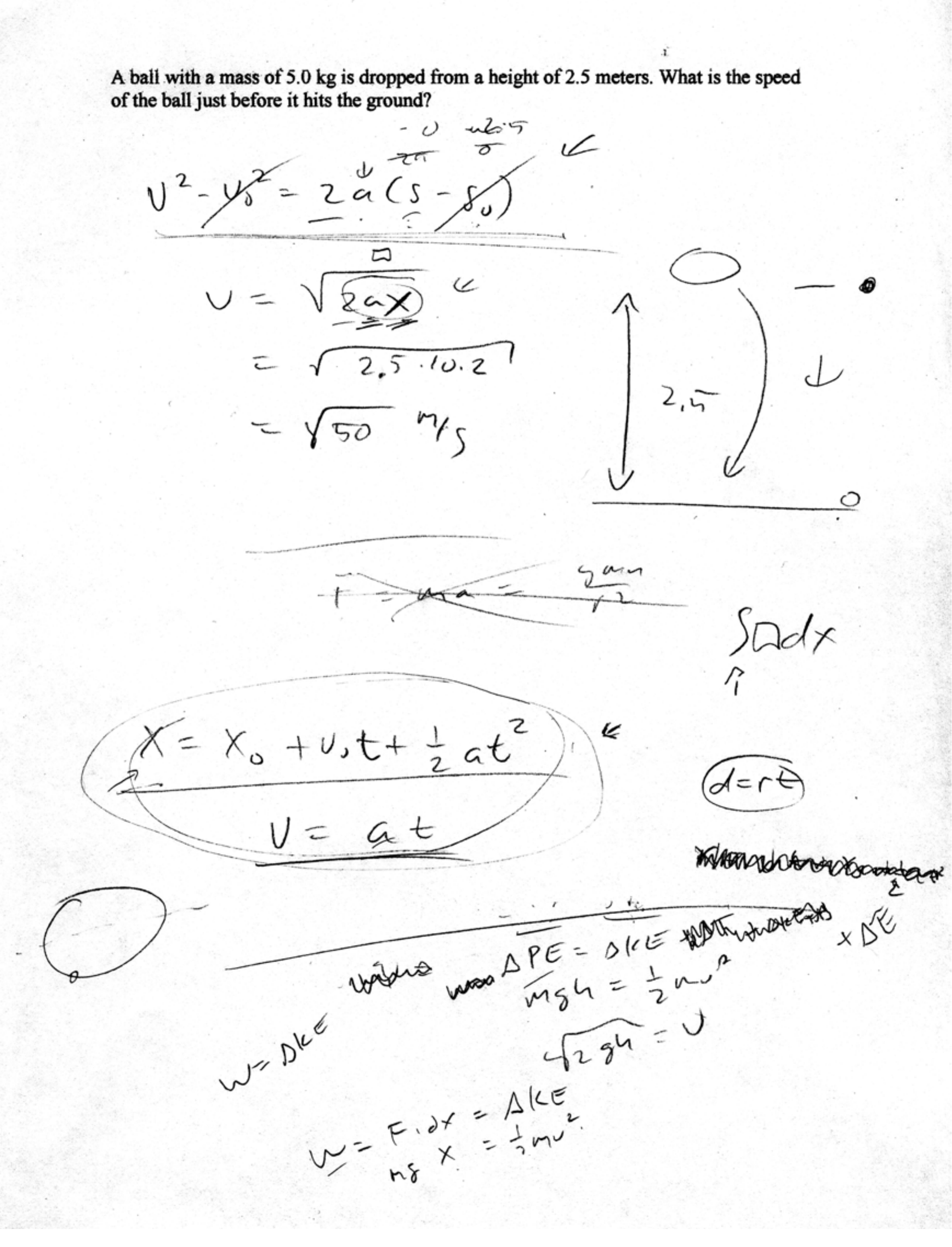
$2g\Delta h$

$V = \sqrt{2ah}$

$\frac{1}{2}mv^2 - \frac{1}{2}mv^2 = mg(\Delta h)$

$\frac{2\cancel{m}g\Delta h}{\cancel{m}}$

Nathan



A ball with a mass of 5.0 kg is dropped from a height of 2.5 meters. What is the speed of the ball just before it hits the ground?

$$v^2 - \cancel{v_0^2} = 2a(s - \cancel{s_0})$$

$$v = \sqrt{2ax}$$

$$= \sqrt{2.5 \cdot 10 \cdot 2}$$

$$= \sqrt{50}\ \text{m/s}$$

$$\cancel{F = ma = \frac{Gmm}{r^2}}$$

$$\int \square\, dx$$

$$x = x_0 + v_0 t + \frac{1}{2} a t^2$$

$$v = at$$

$$d = rt$$

$$W = \Delta KE$$

$$\Delta PE = \Delta KE$$

$$mgh = \frac{1}{2} m v^2$$

$$\sqrt{2gh} = v$$

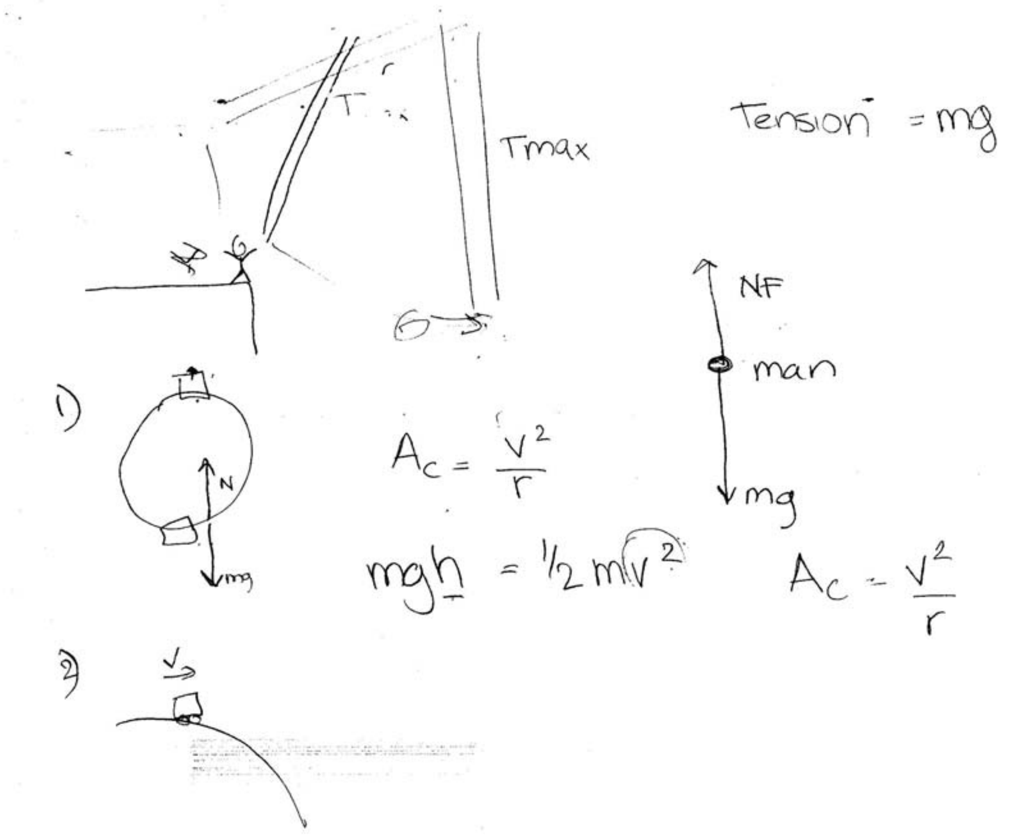
$$\times \Delta E$$

$$W = F \cdot dx = \Delta KE$$

$$mg\,x = \frac{1}{2} m v^2$$

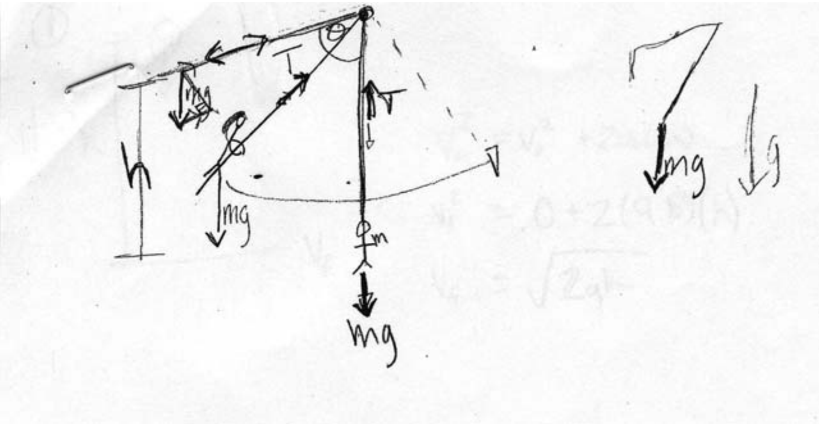
Solutions to the Tarzan Problem:

Zoe

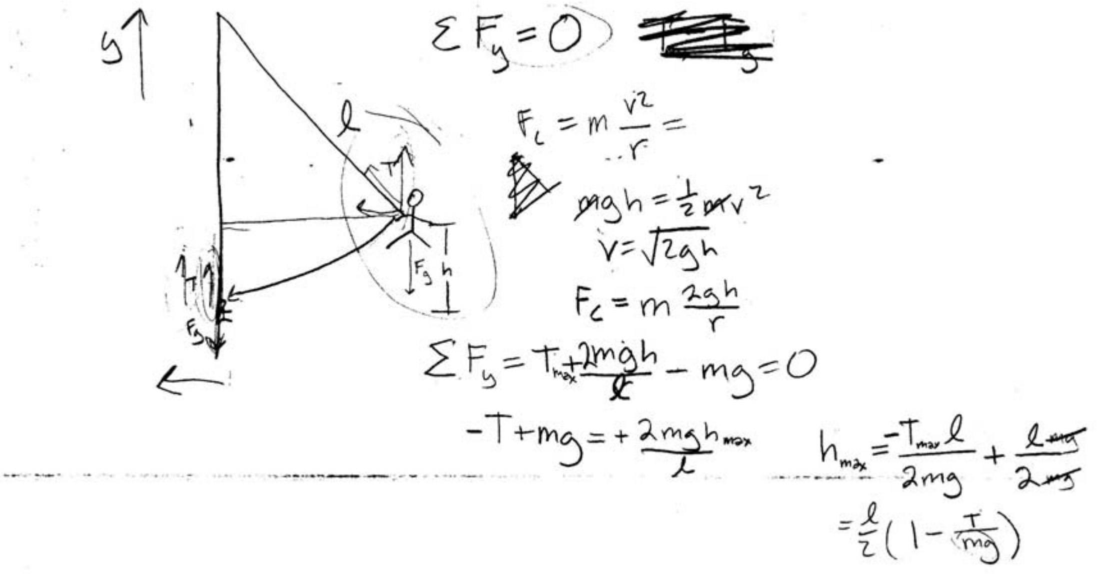


Simon

Jenny



Kaylee



$\Sigma F_y = 0$

$F_c = m\frac{v^2}{r} =$

$\cancel{m}gh = \frac{1}{2}\cancel{m}v^2$

$v = \sqrt{2gh}$

$F_c = m\frac{2gh}{r}$

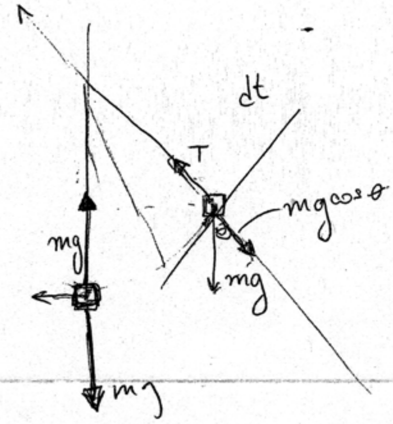
$\Sigma F_y = T_{max} + \frac{2mgh}{\ell} - mg = 0$

$-T + mg = +\frac{2mgh_{max}}{\ell}$

$h_{max} = \frac{-T_{max}\ell}{2mg} + \frac{\ell \cancel{mg}}{2\cancel{mg}}$

$= \frac{\ell}{2}\left(1 - \frac{T}{mg}\right)$

Malcolm

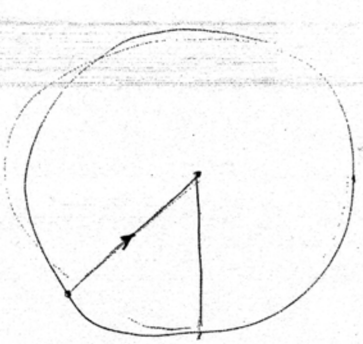


T_{max} = ✓

$$\sqrt{\frac{g}{l}}$$

$$ma_c = \frac{mv^2}{r}$$

$$a_c = \frac{v^2}{r}$$

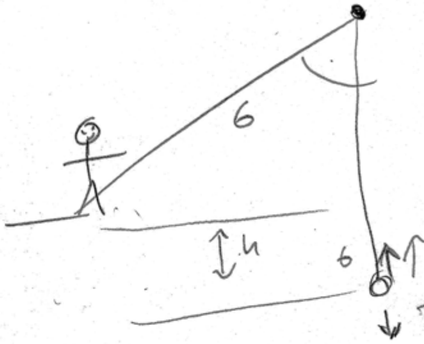


$$T = \boxed{ma_c} = \boxed{\frac{mv^2}{r}}$$

$\delta L = 0 \Rightarrow x(t)$, $v(t)$

Nathan

Tarzan swings on a vine with a length of 6 meters. The vine can experience a tension of 1568 N before breaking. If Tarzan weighs 784 N, what is the maximum initial height that he could swing from without breaking the vine?



$$\frac{mv^2}{r} = F_c$$

$$\downarrow F = 784\,N$$

$$+\ F_c = \frac{mv^2}{r}$$

$$\frac{1}{2}mv^2 = mgh$$

$$v^2 = 2gh$$

$$T \le 1568\,N$$

$$F_T + F_c = F_T + \frac{m}{r}2gh = 784\left(1 + \frac{2h}{6}\right) \le 1568$$

$$h \le \left(\frac{1568}{784} - 1\right)\frac{6}{2} = 3\,m$$

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