APPENDIX E: REFEREED PUBLICATIONS

Journals

Conference Proceedings

Book Chapter

Copies of the pre-prints or manuscripts of each of the publications above are attached.
In science new words might be “invented” to name or describe new processes, discoveries, or inventions. However, for the most part, the scientific vocabulary is formed from words we use throughout our lives in everyday language. When we begin studying science we learn new meanings of words we had previously used. Sometimes these new meanings may contradict everyday meanings or seem counterintuitive. We often learn words in association with objects and situations. Due to these associations that students bring to class, they may not interpret the physics meaning correctly. This misinterpretation of language leads students to confusion that is sometimes classified as a misconception. Research about the semantics used in physics textbooks and the meaning of words, but the problem seems to go beyond semantics. The linguistic relativity hypothesis, sometimes referred to as the Sapir-Whorf hypothesis, says that “we see and hear and otherwise experience very largely as we do because the language habits of our community predispose certain choices of interpretation.” An upshot of this hypothesis is that language may not determine thought, but it certainly may influence thought. We have to make students conscious of the fact that though the words may remain the same, their everyday meaning is no longer a figure of speech, but a technical meaning (physics meaning). That is, we need to change the way students may “think” about words. In spite of the close relationship between language and thought, most research does not address the semantics used in physics textbooks and the meaning of words. This study, however, will address that relationship.

In this paper we present results of a study done at Kansas State University and at the Universidad Autonoma de Yucatan in Mexico. We provide insights on the implications of the use of everyday language in the learning of physics concepts. Our main question is: Do the differences in the use of words between everyday life and physics inhibit learning of physics? We focus on three words that are common in any introductory physics course: force, momentum, and impulse. The following sections describe the goals, methods, and results of our study. In our conclusion we provide some suggestions to help students incorporate the physics meaning of these words into their vocabulary.

Goals and Methods

Our goal was to study how students perceive the similarities and differences between the “everyday” and “physics” meanings of the words force, momentum, and impulse. We were also interested in studying whether these perceived differences and similarities af-
fect the learning of those concepts in physics. A major portion of the data was collected at Kansas State. The participants in our study consisted of 154 students enrolled in The Physical World I course, a course that is taken by nonscience majors, most of whom are in their junior year. *Conceptual Physics* by Paul Hewitt is the text for the course. Fifty-seven percent of the students had previously taken at least one physics course. Through a collaborator at the Universidad Autonoma de Yucatan in Mexico, we carried out a component of our research with native Spanish speakers. We wished to know if Spanish-speaking students have similar problems to English speakers in using their vocabulary for the word *force*. Because of schedule conflicts we were able to study only this word.

Our work at Kansas State consisted of three phases: (1) presurvey, (2) postsurvey, and (3) interview. All 154 students participated in the surveys and 14 were selected for interviews. In the presurvey we asked students to make up three different sentences using the word *force* or variants of it. The term *force* had not been introduced in class at the time of the presurvey. Thus, it showed how the students would use the word in their everyday vocabulary. We sorted the sentences into four classifications according to the usage of the word *force*: Verb Inanimate, when the word is used as a verb and relates to a subject (person or animal); Verb Animate, when the word is used as a verb and relates to an inanimate object; Noun, when the word is used as a noun; and Adjective or Adverb, when the corresponding variant of the word is used as an adjective or adverb. Table I shows the most frequently written sentences of each type.

The postsurvey was administered after the term *force* was introduced in class. For this survey, we chose four sentences from the list and presented them to the students. We asked students to explain the similarities and differences between the use of the word *force* in the given sentence and its use in physics. The results from the second survey were classified into three categories: category 1 included students who can explain how the word *force*, as used in each of the sentences, is both similar to and different from the word *force* as used in physics; category 2 included students who are able to describe these similarities and differences for only a few of the given sentences; and category 3 included students whose responses indicate they cannot explain these similarities and differences for any of the given sentences. The categorization of students’ sentences was validated by an independent researcher. Immediately after the postsurvey, the course instructor administered a scheduled class test that evaluated course material and included the concept of force. In our analysis we focused on the score for the questions relevant only to force—9 out of 26 total multiple-choice questions. Only two of these questions required numerical calculations; the other seven questions were conceptual. These conceptual questions were similar to the ones in the Force Concept Inventory (FCI). This postsurvey was translated to Spanish and applied to freshman engineering students at the Universidad Autonoma de Yucatan in Mexico.

### Table I. Classification of sentences collected from students with the word *force* or a derivative of it. The students are more likely to use *force* as a verb.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Sentence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Verb Inanimate</strong></td>
<td>“I forced the box into the closet.”</td>
</tr>
<tr>
<td></td>
<td>“Jim was forcing the nut on the bolt.”</td>
</tr>
<tr>
<td><strong>Verb Animate</strong></td>
<td>“I forced myself to go to class everyday.”</td>
</tr>
<tr>
<td></td>
<td>“My parents forced me to go to college.”</td>
</tr>
<tr>
<td><strong>Noun</strong></td>
<td>“The force on the ball made it move.”</td>
</tr>
<tr>
<td></td>
<td>“The bomb exploded with great force.”</td>
</tr>
<tr>
<td></td>
<td>“I was hit by the force of the 18 wheeler.”</td>
</tr>
<tr>
<td><strong>Adjective</strong></td>
<td>“She used a very forceful tone of voice.”</td>
</tr>
</tbody>
</table>

### Table II. Classification of sentences collected from students with the words *momentum* and *impulse*. The students use these words only as nouns or adjectives.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Sentence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Noun</strong></td>
<td>“After their touchdown, the other team had the momentum.”</td>
</tr>
<tr>
<td></td>
<td>“The football player had a lot of momentum when he tackled his opponent.”</td>
</tr>
<tr>
<td></td>
<td>“Our team gained momentum in the game after intercepting the ball.”</td>
</tr>
<tr>
<td></td>
<td>“As the car rolled down the hill it gained momentum.”</td>
</tr>
<tr>
<td></td>
<td>“An impulse made her change her mind.”</td>
</tr>
<tr>
<td></td>
<td>“My first impulse was to kick him.”</td>
</tr>
<tr>
<td></td>
<td>“In time of crisis we act on our impulses.”</td>
</tr>
<tr>
<td><strong>Adjective</strong></td>
<td>“My sister is an impulsive shopper.”</td>
</tr>
</tbody>
</table>
The interview protocol at Kansas State was similar to the procedure followed on the written surveys. Students were first asked to write a sentence using the word *force*, then they were asked to explain how the meaning of the word *force* as used in their sentence is similar and dissimilar to the word as used in physics. Later they were presented with a few selected sentences containing the word *force* and asked the same questions.

We followed an identical survey protocol (all three stages) for the words *momentum* and *impulse*. For the results from the second survey of these words, we had only two classifications, Noun and Adjective. Table II shows the most frequently written sentences of each. Immediately after the corresponding second survey, the course instructor administered the scheduled class test, which evaluated these two concepts among others. Because of the course structure the number of questions on these concepts was reduced to six by the course instructor. Thus, to have significance we combined the results from these two words. The questions were multiple choice, three requiring simple numerical calculations and three of the conceptual type. The interviews on these words followed the same protocol as the one on *force*.

**Results and Discussion**

**Force**

Fifty-nine percent of sentences on the presurvey included the word *force* as a verb. This observation is consistent with the fact that *force* is often used as a verb in everyday language.\(^{11,12}\) Thirty-six percent of the students in the second survey were in categories 1 and 2, i.e., they described the similarities and differences between the meaning of the word *force* in the given sentences and its physics meaning. The remaining 64% of the students, category 3, are apparently not able to differentiate between the everyday and physics meaning of *force*. Figure 1 shows the “cumulative frequency” curves for categories 1, 2, and 3 on the second survey versus the students’ test scores. From it, 80% (80th percentile) of the students in category 1 have grades below 91, the same percentages of students in category 2 have grades below 89, and from category 3, grades below 84. Thus, students who could identify and explain the physics meaning of the word *force* obtained better test scores. We believe this establishes a link between the linguistic ability of students to discern various meanings of *force* and their conceptual understanding of the concept of force, as measured by the test. To further probe our results, we interviewed 14 students individually, using representatives from each of the three categories. The students first wrote two sentences using the word *force* (or its derivative). They were asked to think aloud about their sentences and describe whether the ways in which they had used *force* were similar or different from the ways in which they used it in everyday life. All students were able to identify whether the way they were using *force* had an everyday or physics meaning. When asked why the word *force* in one of their sentences would have a physics meaning, they responded by stating that the word relates to pushing, pulling, or motion. When asked why it would have an everyday meaning, they said it has to do with mental power, power, or following rules—not in a physical sense. Their explanation for the physics meaning is consistent with what they were taught in class: *Force* is “any influence that tends to accelerate an object; a push or a pull.” They also were taught that force equals mass times acceleration. Only two out of the 14 students were able to relate force to the mass of the object and/or its acceleration. In the second part of the interview, the students were given four sentences and asked to identify the meaning of the word *force* in each sentence. All students were able to identify whether the meaning corresponded to everyday life or
physics because they focused on the context of the sentence. However, almost all students were unable to explain how the meaning of the word is similar to or different from its physics meaning. Only two students who identified force with mass and/or acceleration were able to explain the similarities and differences of the meaning of force in the sentence with its meaning in physics. Thus, all students were able to explain whether the word force in the sentences has an everyday or physics meaning, but only those who identified the parameters associated with force were able to explain how the word force in the sentence was similar and different to its use in physics. For example, when a student was asked to explain the meaning of the word force in the sentence “The bulldozer forced the rock into the ditch,” he answered, “The bulldozer has direct contact onto [sic] the rock, pushes the rock.” He identified force as a push, from the definition of force. Another student stated that “Force causes movement, there are forces everywhere, like friction. Force is mass times acceleration.” When this student was asked to explain the meaning of the word force in the bulldozer sentence, she said, “The bulldozer moves the rock into place, there is mass and acceleration.” This last student is using the parameters involved in force to explain why the word force in the sentence has a physics meaning. She is attempting to assimilate the meaning of the word.

We obtained some interesting results from the surveys given to undergraduates in Mexico. We found that Spanish-speaking students in Mexico are very likely to use the word fuerza (force) as a synonym for poder (power) in the sense of “ability to act or produce an effect,” i.e., they use the word force as a verb (forzar), which is similar to the way English-speaking students at Kansas State responded to the same survey. We believe this similarity in results is because the word fuerza is spelled similarly to the word forzar, which is a verb—in English the word force is used both as noun and verb. Thus, it seems that students are more familiar with the verb usage, the everyday meaning. In terms of the Sapir-Whorf hypothesis, the language habits predispose a choice of interpretation. We infer from this that it is possible that if we had administered these surveys to Italian-speaking students, where the words are forza for noun and forzare for verb, we would have found the same results. In contrast, we would expect that students with a native language where the noun and verb forms of the word force are different could make the distinction. For example, in German kraft is force as a noun and erzwingen is force as a verb.

**Momentum and impulse**

Momentum and impulse were discussed in class after the topic of force. Eighty percent of the sentences written by the students used the words momentum and impulse as a noun in the presurvey. This is consistent with the common usage of these words in everyday language. On the postsurvey 36% of the students were placed in categories 1 and 2. That is, they were able to differentiate between the everyday and the physics meaning of the words and explain the physics meaning. This is the same percentage of students that resulted in the postsurvey for the word force, although our records indicate they are not the same group of students. Figure 2 shows the “cumulative frequency” curves for categories 1, 2, and 3 on the second survey versus the students’ test scores on questions pertaining to the concepts of momentum or impulse. Eighty percent (80th percentile) of the students in category 1 have grades below 90, category 2 score 80, and category 3 score 60. Thus, students who can identify and explain the physics meaning of the words momentum and impulse (category 1) obtain higher test scores.
category 3 grades below 60. In general, students in category 1 score higher on the test than students in categories 2 and 3. These results are very similar to the ones for the word force, reinforcing the idea of a link between the linguistic ability of students to discern various meanings of a word and their conceptual understanding of the word. The difficulty with these words also showed in the test scores of the students.

The participants in the interview phase were the same students as before. We asked them to write two sentences using the word momentum and two with impulse. Twelve students interpreted the meaning of the word momentum in the physics context. However, only six of them related momentum to mass and/or velocity. When asked to explain momentum in physics, typical answers included terms such as “the mass of the object, speed, action, motion, or build up of energy.” When relating to an everyday meaning, the students said momentum had to do with feelings or mental action, not physical motion. It is interesting to note that momentum has a Latin root that means “movement,” so this word by itself relates to motion. The everyday meaning of the term is quite similar to its physics meaning. It appears that due to this similarity in meanings, students are more likely to explain the physics meaning of the term momentum. For instance, when asked to explain the meaning of this term, one student said, “When someone is running, he has mass and speed, he is creating momentum.” Another said, “Momentum in physics is... as something falls speed up. In a slope gains speed, gains momentum.”

Only one of the students was able to explain the meaning of the term impulse as used in physics. The other students used the everyday meaning of the term. They said impulse has to do with instant action, spontaneity, or something you do without thinking about it. The dictionary meaning of the word impulse is: a sudden spontaneous inclination or incitement to some usually unpremeditated action. This word is very well embedded in students’ minds and it is difficult for them to relate it to physics. In fact the physics meaning of the term, product of the force acting and the time duration for which it acts, is quite different from the everyday meaning. It appears that this difference makes it difficult for students to understand the word’s physics meaning. When the two students quoted above were asked to explain the meaning of the term impulse, the first student said, “Impulse is something involuntarily [sic], it just happens.” The second student said, “Impulse is a force, a push, ... not sure.” The first student is describing the everyday meaning, but the second student, albeit doubtfully, is relating impulse to force. This is the only student who did not relate impulse to instantaneous actions.

Thus, the word momentum seems more intuitive to the students. They might not define it as velocity times mass but they always relate it to motion. The word impulse is not as intuitive to the students, because its everyday meaning is quite different from its meaning in physics. Again the Sapir-Whorf hypothesis1 seems to be applicable here since it is the everyday meaning of these words that is the most influential in students’ thoughts.

Impact on Instruction

One way the acquisition of knowledge can be conceptualized is through the idea that students acquire different understandings of relevant concepts. These coexist and compete with previous informal understandings.14 We propose the idea that comparing everyday and physics meanings of words will help students to assimilate the meaning of the word in physics. When making these comparisons the students can relate to the parameters involved in the physics term, thus helping them to establish connections between the words and building their “physics vocabulary.” We do not believe the physics meaning of words will take the place of the everyday meaning, but rather they would coexist. Students can be asked to compare the physics and everyday meanings of the words by writing essays in different contexts.15 Many of the students in conceptual physics classes, such as humanities majors, have strong writing abilities and may find such tasks to be quite enjoyable. Efforts to inculcate superior writing skills across the curriculum have been used in several high schools and colleges. The writing exercises described above may be helpful in such a curriculum.

Conclusions

We surveyed a physics class with nonscience majors to study students’ perceptions of the similarities between the everyday and physics meanings of three
commonly used words. Our findings show that students who can differentiate between the everyday and physics meanings of the words, and can explain the physics meaning, are more likely to obtain higher test scores. From interviews we conjecture that students who are able to identify or remember parameters related to the word are more likely to explain its physics meaning. In addition we found that even in other languages where the word force can be used as verb or noun, students are more likely to use it in an everyday connotation. For the other two words included in our study, we found that the word momentum seems more intuitive to the students, as they always related it to motion, whereas the word impulse is not as intuitive to the students; its everyday meaning is quite different from its meaning in physics. Unfortunately the idea of looking at differences between everyday and physics meanings of the words seems not to be carried out from force to momentum and impulse; the tests scores for the last two words are lower (Figs. 1 and 2).

Our results also indicate that physics instructors should be more cognizant of the use of language and the alternative meanings of physics terminology that their students bring with them to class. We propose that instructors can devise special writing assignments that would enable students to overcome this linguistic barrier in learning physics.

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References

PACS codes: 01.40R, 01.55, 01.90

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Students’ models of Newton’s second law in mechanics and electromagnetism

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Abstract

We investigated students’ use of Newton’s second law in mechanics and electromagnetism contexts by interviewing students in a two-semester calculus-based physics course. We observed that students’ responses are consistent with three mental models, Newtonian, Aristotelian, and a hybrid model formed with elements of the first two models. These models appeared in mechanics contexts and were transferred to electromagnetism contexts. We developed an inventory to help instructors identify these models and direct students towards the correct one.

1. Introduction

Perhaps the most important topic taught in classical mechanics is Newton’s laws. Newton’s second law, ‘\( F = ma \)’, has preoccupied authors for years [1–9]. Previous research has suggested that students bring their own understanding of the physical world into the classroom [10], making the teaching and learning of Newton’s laws a challenge [11]. Research also shows that acquisition of knowledge does not happen immediately. One way the acquisition of knowledge can be conceptualized is that students acquire different understandings of relevant concepts, which coexist and compete with previous informal understandings [12]. It has been suggested that teachers should be prepared to draw on their students’ prior understanding and help them to shape it into one that reflects accepted scientific knowledge [13]. Cognitive science finds that people tend to organize their experiences and observations into patterns or mental model(s) [14]. Thus, by investigating what mental models students use for physics concepts and making this information accessible to teachers, we can help them build upon their students’ understanding.

In this paper we present part of our research on students’ mental models of Newton’s second law. We have probed whether students apply these models consistently across various contexts.
contexts, through two consecutive semesters of physics, addressing concepts in mechanics and electricity and magnetism. This kind of research has not been done previously in electricity and magnetism contexts. We found students used three models for Newton’s second law: the Newtonian model (‘\( f = ma \)’), the Aristotelian model (‘\( f = mv \)’), and a hybrid model that combines the Newtonian and Aristotelian models. In section 2 we present definitions for the main terms we use in this work. Section 3 describes our research methodology, section 4 presents our results and in section 5 we discuss pedagogical applications and conclusions.

2. Mental models

We use the term mental model to refer to an internal representation, which acts as a structural analogue of situations or processes. Its role is to account for the individuals’ reasoning when they try to understand, explain and predict physical world behaviour [15]. We consider mental models consist of more fundamental cognitive and knowledge elements, e.g. p-prims [16, 17] or conceptual resources [18, 19]. These elements are assembled consistently and are often called features or aspects of the model [20]. A few characteristics of mental models include the following:

1. they consist of propositions, images, rules of procedure and statements as to when and how they are to be used;
2. they may contain contradictory aspects;
3. they may be incomplete; and
4. aspects of a mental model do not have firm boundaries; therefore similar aspects may get confused [21].

The mental models used by the student must be understood in terms of their own internal consistencies, not as ‘errors’ when compared with an expert’s model. Mental models used by the students may depend on the context of the problem, e.g. mechanics or electromagnetism. It is possible for a learner to use several different, yet stable and coherent, explanatory elements when tasks are related to different contextual settings pertaining to the same concept [22].

Several studies of students’ intuitive ideas about motion and forces have been conducted [23–31]. Researchers have found that students generally use two ways of thinking about Newton’s second law: ‘Newtonian’ and ‘Aristotelian’: Newtonian when students recognize that a constant non-zero net force on a body causes it to increase speed and/or change its direction of motion (\( f = ma \)) [23, 24], and Aristotelian when students conclude that every motion has a cause; an increase in speed is achieved by an increase in force (\( f = mv \)) [23, 24]. These common ways of thinking meet the definition of mental models; therefore, in this paper we will refer to them as the ‘Newtonian’ mental model and the ‘Aristotelian’ mental model. In our research we also found some of our students used aspects from these two main models. We called this new way of thinking a ‘hybrid’ mental model [20, 32]. Students who consistently used any of these three mental models throughout an interview are considered to be in a ‘pure mental model state’. Conversely, students who used more than one mental model during a single interview are considered to be in a ‘mixed mental model state’ [33]. In this paper we will also say that the students use a pure mental model or a mixed mental model.

3. Goals and method

The overarching goal of our research is to develop a multiple-choice instrument, a mental model inventory that allows educators and researchers to probe the mental model states of large numbers of students. To develop such an instrument, we began by exploring the knowledge structures that students use in several contexts through in-depth interviews. Our interviews addressed three main research questions: (1) are the students consistent in their application of mental models? (2) are students’ mental models context dependent? and (3) do particular variables trigger a student’s choice of mental model? We interviewed a cohort of 16 students in a calculus-based physics class six times over the two-semester course sequence. The class
operates in a studio format with two 1 hour lectures and two 2 hour laboratories integrated with the recitation. The students were volunteers who received monetary compensation. The entire class section consisted of 240 students; majors in different engineering areas, physics and math. About 90% of the students had physics in high school and approximately 5% have taken a physics class at the college level to prepare for the calculus-based physics class, which normally is taken in the sophomore or junior year. About one-third of the students were women. The interviews were tape recorded and lasted between 30 and 45 min. We proceeded in two phases: phase I occurred during the first semester when classical mechanics was covered and phase II occurred during the second semester when electricity and magnetism were covered. In phase I, 11 men and five women participated in the study. The first interview was conducted prior to instruction on Newton’s laws, early in the semester. The second interview was conducted after instruction on Newton’s laws, and the third interview was conducted near the end of the semester. The contexts used in the interviews will be discussed in the next section. In phase II we had ten male and six female participants. Interview 4 (first interview in phase II) was conducted after instruction on electric fields. Interview 5 was conducted after instruction on magnetic fields, and interview 6 after instruction on induction. Ten of the students—six men and four women—participated in both phases, completing all six interviews. For the purpose of this paper we limit our analysis to the results from these ten students. This sample size is considered appropriate for this type of research [35].

4. Results and discussion

The protocol for phase I interviews included two contexts: vertical and horizontal. We used the well known ‘force concept inventory’ (FCI) [36, 37] as the basis for our research questions. FCI questions 25, 26, and 27 were used for the horizontal context: a woman exerting a constant horizontal force on a large box. As a result, the box moves across a horizontal floor at a constant speed. Question 17 was used for the vertical context: an elevator is being lifted up in an elevator shaft at constant speed by a steel cable. Each student received a sheet of paper with a figure depicting the problem, a statement of the problem and one or two questions. They were given the opportunity to write notes or make drawings in order to explain their answers. Table 1 presents the protocol question for both contexts and figures 1(a) and (b) show the figures representing the problem.

The three variables explored in these contexts are the magnitude of the force, the mass and the speed of the object. Table 2 shows the students’ models through the first semester. An example of a student using the Newtonian model in the horizontal context, interview 1, is student S3. Student S3 responded to question 1, ‘it is moving at constant speed, is not
Table 1. Questions asked to students in interview 1 of phase I, mechanics.

<table>
<thead>
<tr>
<th>Horizontal context</th>
<th>Vertical context</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) How does the force exerted by the woman compare with other forces acting on the box?</td>
<td>(1) How does the force exerted by the cable compare with other forces acting on the elevator?</td>
</tr>
<tr>
<td>(FCI no 25)</td>
<td>(FCI no 17)</td>
</tr>
<tr>
<td>(2) How will the speed change if her force is doubled?</td>
<td>(2) What is (are) the force(s) acting on the elevator when (a) it is held at rest? (b) it is moving up or down at constant speed</td>
</tr>
<tr>
<td>(FCI no 26)</td>
<td></td>
</tr>
<tr>
<td>(3) What force is needed to double the speed?</td>
<td>(3) What is the force if the speed is doubled?</td>
</tr>
<tr>
<td>(4) What force is needed to steadily increase the speed?</td>
<td>(4) What is the force if the speed is steadily increasing?</td>
</tr>
<tr>
<td>(5) What happens if she stopped pushing?</td>
<td>(5) How does the speed change if the force is doubled?</td>
</tr>
<tr>
<td>(FCI no 27)</td>
<td></td>
</tr>
<tr>
<td>(6) What would happen if she exerts the same force on two boxes, one of top of the other?</td>
<td>(6) What force is needed to move an elevator twice as massive at the same speed?</td>
</tr>
</tbody>
</table>

Table 2. Students’ models in interviews, phase I. The ‘A’ indicates ‘Aristotelian’ model; ‘N’ indicates ‘Newtonian’ model and H indicates hybrid model.

<table>
<thead>
<tr>
<th>Interview/context</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
<th>S10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/horizontal/vertical</td>
<td>H</td>
<td>H</td>
<td>N</td>
<td>H</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>2/horizontal/vertical</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>A</td>
</tr>
<tr>
<td>3/horizontal/pulleys</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>N</td>
<td>N</td>
<td>H</td>
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<td>H</td>
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<tr>
<td></td>
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<td>N</td>
<td>N</td>
<td>H</td>
<td>N</td>
<td>N</td>
<td>A</td>
<td>N</td>
<td>H</td>
<td>A</td>
</tr>
</tbody>
</table>

accelerating . . . the woman’s force has to overcome friction for the box to start moving, but once moving the forces are equal’. The same student responded to question 2 in the vertical context, part (a), ‘the steel cable has a force on the elevator . . . and gravity. Because it is at rest they are equal’. Part (b) ‘there is gravity and the force by the cable . . . the upward force is greater because it is moving up. The force from the cable is larger than it was at rest . . . gravity is bigger than the force of the cable, gravity does not change . . . the cable is not exerting as much of an upward force’. In the last context S3 is using the Aristotelian model; the elevator is moving up or down, therefore the biggest force must be in that direction. Observe that S3 responded to question 1 in the horizontal context by stating the condition of constant speed, while in response to question 2 in the vertical context there is no reference to this condition. This student used the Newtonian model for the horizontal context, but Aristotelian for the vertical context; therefore, we say the student uses a mixed model state in mechanics contexts. An example of a student who used the hybrid model is S7. S7 responded to question 2 in the horizontal context, ‘it [the box] will go faster . . . it would increase its speed to about twice because it is twice the force . . . it [the speed] increases and then it will become steady to twice the speed [sic]’. It is clear that S7 used a combination of Newtonian and Aristotelian models in this response; that is the hybrid model. For the vertical context S7 used the Aristotelian model, thus S7 used a mixed model state in mechanics contexts on the first interview.

The protocol for interview 2 included the same two contexts, horizontal and vertical, plus variants: (1) a woman pushing a box across a horizontal floor (original); (2) a woman pulling a box; (3) a bulldozer pushing a box; (4) a motor pulling a box—with a string; (5) a motor pulling up a box with a cable (originally an elevator); (6) a forklift raising a box vertically, (7) a woman lifting up a box; and (8) a woman standing in a balcony pulling a box with a cable. The variables explored in these scenarios are the same as in interview 1. The interview occurred a
few weeks into the term. By this time the students had received two lectures and performed two laboratory activities on Newton’s laws. Two students made unexpected changes in their mental models (table 2). One student (S10) remained in a pure Aristotelian state, while the other (S4) moved from a mixed model state to a pure hybrid state. The other eight students moved to or remained in a pure Newtonian state. These eight students used the line of reasoning ‘constant speed means no acceleration, that is no net force; then the forces are equal’. Students S4 and S10 did not use this logic. Therefore, we believe that, by failing to recognize this idea, students S4 and S10 did not improve like the other students. S4 did recognize the idea of constant speed as implying equal forces, but when the question about ‘double the force’ or ‘double the constant speed’ was asked, S4 used the Aristotelian model. We noticed that the change in the magnitude of the force and speed as variables induced a student to use the Aristotelian model. This finding is in accordance with other researchers’ findings in other contexts [24]. Students used formulae and free body diagrams before attempting to respond to the questions. One of them pointed out that ‘the formulae give me a guide for answering questions’. However, another student showed that having a list of formulae might not be of much help at all. Student S10 used the formula \( f = \frac{1}{2}mv^2 \) to respond to our questions. At the time S10 was interviewed the students had covered some energy topics in lecture. S10 drew responses from a wrong formula. We asked the students whether they considered the horizontal context problems different from the vertical contexts. The general response was ‘you just need to think logically, they are the same, forces are forces’. We also asked whether any particular context was more challenging and what kind of problem was most difficult. The general consensus was ‘forces in a horizontal or vertical plane are the same, the only thing [sic] . . . friction is different from gravity’. And ‘. . . inclined planes . . . you have to work out the components’.

For the final interview in phase I we again used the slightly modified horizontal context—a block on a table pulled using a rope. We also used a modified Atwood machine—pulleys (figure 2). Research has shown that this last context poses difficulties to students [28]. The variables explored in the interviews were again force, mass and speed. Table 2 shows students who used the Newtonian model on interview 2 did not necessarily continue using this model. For instance, student S7 switched from using the pure Newtonian model in interview 2, to using a mixed model (hybrid and Aristotelian). Once again the questions that caused the students to use the Aristotelian model were related to ‘double the force’ and ‘double the speed’. When we asked what is the force used to pull the block at a constant speed, the response was invariably ‘the force equal [sic] to friction . . . in opposite direction’. The students who continued using the Newtonian model also used the line of reasoning ‘no acceleration, no net force’. Thus, regarding mechanics contexts, the model used by the students depended on the context and not much on when (time frame) the contexts were explored. The idea of ‘no acceleration, no net force,’ brought up by students after instruction played an important role in their reasoning.

During the spring term we conducted phase II of our research. The second semester of the course traditionally starts with electrostatic concepts and then moves to magnetism [34]. The fourth interview (first in phase II) in our research was conducted after instruction on electric fields. Our interest was not the students’ knowledge on electric fields, but their use of Newton’s second law. As the basis for the electric field context we used question 10 from

![Figure 2. Pulley system used in protocol for interview 3 (Atwood’s machine). Masses 1 and 2 are identical.]
the conceptual survey in electricity and magnetism (CSEM) [38] with slight modifications: a positively charged sphere is released from rest in a region with a uniform electric field (figure 3). A second problem statement within this context was a positively charged sphere moves at a constant speed in a uniform electric field. The questions focused on five variables—the magnitude of the field, the mass, the magnitude of the charge, its sign, and the speed. Table 3 shows the questions asked in this context. For the second problem we added one more question: If the speed of the sphere is twice the original, how does the $E$ field change? Following our protocol from phase I, all students received a sheet of paper with a figure, the statement of the problem and two questions. To continue exploring whether the students’ models change with time, besides context, we gave the students two problems relating to phase I—the horizontal context FCI question 25 [36, 37] and a box sliding from an inclined plane. The question was, describe the force(s) acting on the box. We found that two months after the last interview students who used the Newtonian model continued to do so. They still used the line ‘no acceleration, no net force’. Student S1 responded to question 1, in the case where the sphere moves at constant speed: ‘My instincts from mechanics ... say constant speed is net force equal zero ... so there is a force from $E$ to the right (looking at the figure on the paper) some force should be pushing to the left ... I am not sure what force (referring to the force to the left)’. For this student the $E$ field context was asked before the FCI question, so no triggering by mechanics contexts can be claimed. Table 4 shows the models used by students during phase II. Thus, though electric field contexts are not frequently related to the use of Newton’s laws, students did use the Newtonian model, when appropriate, if they recalled basic principles. A few of the students used the equation $F = qE$ and drew arrows before responding. All students answered that the force is proportional to the magnitude of the charge and that of the electric field. When we asked question 4, double the mass of the sphere, we did not give clues as to the size of the sphere. A few of the students commented that in ‘this class’ (referring to their physics lecture) ‘mass is negligible’. We do not know if this idea came from their instructor or through solving problems. However other students did consider the mass of the sphere and gave appropriate answers by using $F = qE = ma$.

For interview 5 we used a similar protocol to the one for electric fields, but instead of electric field we used uniform magnetic fields $B$. In the first problem the charged sphere was set at rest. In the second problem the sphere moves at constant speed with a horizontal direction.
Newton's second law mental models

Table 4. Students’ models in interviews, phase II. The ‘A’ indicates ‘Aristotelian’ model; ‘N’ indicates ‘Newtonian’ model and H indicates hybrid model.

<table>
<thead>
<tr>
<th>Interview/context</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
<th>S10</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/horizontal/ Efield</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>N</td>
<td>N</td>
<td>A</td>
<td>N</td>
<td>N</td>
<td>A</td>
</tr>
<tr>
<td>5/B field</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>A</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>H</td>
</tr>
<tr>
<td>6/induction</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>N</td>
<td>N</td>
<td>H</td>
<td>N</td>
<td>N</td>
<td>H</td>
</tr>
</tbody>
</table>

into an area with a magnetic field with the same direction; and the third problem differs from the second in that the direction of the magnetic field is perpendicular to the velocity of the sphere. The interviews were conducted after instruction on B fields. To identify what model students used, we took into account only the way they used forces. When the sphere was set at rest, three of the students responded by considering an E field instead of a B field; that is, they explained that there is a force in the direction of the field, instead of no force since the sphere was set at rest. Two of these students changed their answers later when we brought up the second problem statement; the idea that the sphere must have a speed to have force acting upon it came back to them. We noticed that students again used formulae before answering the questions. For example, student S8’s response to the question ‘describe the force(s) acting on the charged sphere (when the sphere is at rest)’ was ‘the speed is zero, and \( F = qV \times B \) . . . the magnetic field cross the speed is equal zero . . . so no force is acting on the charged sphere, no force is no acceleration, the sphere does not move’. The line of reasoning ‘no force–no acceleration–constant speed’ is present. Student S9 also responded to this same question using the same line of reasoning. However, when the same question was asked in the case where the magnetic field’s direction is perpendicular to the velocity’s direction, student S9 responded: ‘the sphere cross the direction of B [sic] . . . B in the y direction when sphere enters the field region the force is out of the page (gestures of using right-hand rule). The motion of the sphere is \( F = qVB \) . . . As the particle enters it will come out . . . it will come out at constant speed’. Student S9 is one of the students who has used the line ‘no force–no acceleration–constant speed,’ but failed to use it correctly in this context. Again, the context does influence the model students use (table 4).

In the final interview we explored the context of induction. We used two typical problems. The first one was a loop is pulled, with constant speed, out of a region with a uniform magnetic field \( B \). The second was a rod of length \( L \) moves at constant speed on two rails in a uniform magnetic field \( B \) [34, p 718, 740]. We asked two questions for each problem. The first question was to describe the forces acting on the loop (or rod). The second question related forces and motion of the loop (or rod) when pulling was stopped (or the \( B \) field is turned off). In addition we asked the students about how their thinking on these problems related to their first semester course, especially about Newton’s second law. Table 4 shows that none of the students used the Aristotelian model on the induction context. We could claim that the students moved forward on their understanding since the use of a hybrid model implies the use of aspects of the Newtonian model. However, students S7 and S10 switched from the Newtonian to the hybrid model. To find what might have caused this change we carefully reviewed student S10’s transcript. S10 responded to the question related to turning off the \( B \) field on the rod problem ‘well, there is no longer a \( B \) field, since the force \( F = IL \times B \) is zero . . . the rod should come to a stop’. S10’s response to the extra questions was: ‘I do not remember using Newton’s second law . . . uh . . . \( F = ma \) (respect to the motion of the rod) . . . If there is a force there must be an acceleration, and if there is one force there is no net force’. We concluded that student S10 forgot about the meaning of ‘net force’ or perhaps has not understood its meaning. S10 used the Newtonian model only in the \( B \) field context.
5. Teaching implications and conclusions

We found that students solved problems related to Newton’s second law using two main mental models labelled ‘Newtonian,’ and ‘Aristotelian’. They also used a third model which we labelled hybrid model. When a student used only one of these three models in an interview it is said that the student used a pure mental model. When the student used more than one model, it is said that the student used a mixed model. Other authors say the students are in a pure or mixed mental model state [32, 33]. In tables 2 and 4 we follow the progress of ten of the students through different contexts and time. In the first semester, before instruction, only one student (S5) used a pure Newtonian model. After instruction six more students used the pure Newtonian model. Perhaps the most important idea that produced this change was the line of reasoning: ‘constant speed means no acceleration, that is no net force; then forces are equal’. The Aristotelian and hybrid models were mostly triggered by questions relating to double the force, double the mass or double the speed; perhaps because of the word ‘double’ which indicated proportionality. Students transferred their models to the second semester. Seven of the students used a pure Newtonian model on the first interview of phase II. This was expected since the students had received instruction on Newton’s second law. It is also important to note that in electromagnetism contexts, when students are faced with abstract contexts, they are more likely to base their responses on instruction and not on intuitive reasoning as they might do in mechanics contexts. The understanding of basic concepts like ‘vector’ and vocabulary such as ‘net force’ also has a role in the model a student might use. It is important that the instructor reviews concepts and vocabulary for Newton’s second law. Students might be using incorrect models because of the misunderstanding of the background and not because of the misunderstanding of Newton’s second law. For the transfer of models from electromagnetism to mechanics contexts, it is important how electromagnetism contexts are introduced. Some students considered that the transfer of Newton’s laws from mechanics to electromagnetism contexts was not clear. They pointed out that in most of their homework problems mass is negligible, things are small, and there are many approximations.

With the results of these six interviews we have developed a mental model inventory (multiple-choice instrument). This inventory is a tool for instructors to help them determine the models students use; then the instructor can use the information to tailor a class to correct the students’ models. The inventory consists of five surveys that address the same contexts as our interviews. Each survey has five to eight questions with four or five options. The options refer to the possible models students might use. The number of questions is short to facilitate use of the surveys in class. If the instructor uses a personal response system, (s)he could obtain immediate feedback on the model students used. Survey 1 focuses on the contexts of interview 1, horizontal vertical contexts. Survey 2 focuses on Atwood’s machines, survey 3 on electric fields, survey 4 on magnetic fields, and survey 5 on induction. The surveys can also be used as an assessment tool and possibly to continue research on mental models. The entire inventory is available online as portable document format (PDF) files at http://web.phys.ksu.edu/surveys or by e-mailing srebello@phys.ksu.edu.

Acknowledgments

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Try giving one of your students a battery, a bulb and some wires and ask them to make the bulb light. You will find that this simple task will cause many students great difficulty. James Evans\(^1\) notes the low success rate of performing this task among high school seniors, university students, and university graduates. McDermott and Shaffer\(^2\) suggest that students who have difficulty with the bulb-lighting task fail to understand and apply the concept of a complete circuit. Evans, however, asserts that “most of the students have no idea of the way the various wires inside a light bulb are connected. Lacking this understanding, how secure can they be in their understanding of ‘circuit’?”\(^3\) Yet, no research to date suggests how students think the wires inside a light bulb are connected.

Research\(^4\) indicates that students have difficulty lighting a bulb given one wire, a battery and a bulb. Does this result truly indicate that they do not understand the concept of a complete circuit as previous researchers have suggested? Or is it more that they do not know how a light bulb is wired internally? Furthermore, what do we, as physics instructors, mean by the term “complete circuit?” It is generally not a term that is
explicitly defined in introductory textbooks. Students who were interviewed define it as “a complete path for _____ (energy, current, etc.) to move with no breaks.” By this definition, a short circuit is also a complete circuit. We disagree with the inference of McDermott and Shaffer which suggests that a student who makes a drawing as shown in Fig. 1 (Circuit 1), or who cannot make a bulb light given a battery and one wire does not understand the concept of a complete circuit. We contend that the student does not understand the internal wiring of the light bulb and may have difficulty identifying a short circuit. In some respects the drawing itself is confirmation that the student understands a complete circuit; otherwise, the drawing would look like that in Fig. 1 (Circuit 2). There is a complete path for the charges to flow – it simply does not flow through the bulb. We as educators need to be more precise in our definition of a complete circuit. At present, its meaning is hidden from the students and not clearly defined in our textbooks. We suggest the following definition:

A complete circuit is any complete path in which charges can move having no breaks or gaps. A short circuit is also a complete circuit; however, it is not an advantageous circuit as the element that is intended to receive charge does not because the charges are following the path of least resistance, and therefore, bypassing the element.

This paper will present the results of a one-question survey to ascertain students’ ideas of the internal wiring of a light bulb. We have already suggested a useful definition of a complete circuit and will offer a set of promising activities to help students better understand how a light bulb works, strengthening their idea of a complete circuit and enabling them to determine where the contact points are on a light bulb and a socket.
So How Do Students Think a Bulb Is Wired Inside?

In order to answer this question, a one-question survey was created which asked students to draw the location of the wires connecting to the base of a light bulb (see Fig. 2). The survey was given to 124 first semester introductory calculus-based engineering students, and 149 first semester introductory algebra-based general physics (GP) students at Kansas State University (KSU) in the spring 2003. The results from the survey and additional data from ten interviews with introductory conceptual physics students are presented in Table I. One intriguing observation is that the results for the calculus-based and the algebra-based students are almost exactly reversed. There appears to be an effect from the level of the physics course taken. More research will need to be done to uncover precisely why this is so; however, this is not the focus of the present paper.

Insert Table I and Figure 2 here

“Making Sense of Incandescence”

From Table I, it is clear that over 50% of our general education physics students have an incorrect image of the internal wiring of a light bulb. So, how does an instructor
help a student develop the correct view of the internal wiring of a light bulb? We would like to suggest the following three activities, which we have chosen to call *Making Sense of Incandescence.* These activities are not intended to replace traditional circuit activities, but to make them more effective by strengthening the students’ understanding of a complete circuit and developing the correct view of how a light bulb is internally wired and how it operates. These activities grew out of the interview protocol used with the conceptual physics students. They were initially developed for and pilot-tested with students at a local high school in Kansas, but have since been used with university level conceptual physics and general physics students. “Making Sense of Incandescence” loosely follows the learning cycle, which has three components: an exploration (Bright Ideas), a concept introduction (Activity 1: Getting Hot; Activity 2: That Glowing Feeling; and Activity 3: Getting Connected), and an application (Lighting Up the Night). The activities are done in stations. The activities will now be described in more detail.

The exploration activity, Bright Ideas, elicits the students’ initial ideas about the concepts that are presented in the remainder of the activities and serves as a baseline to see what conceptual changes occur during the activities. Students are asked to describe how a light bulb works, how they believe the wires are connected to the base (given Fig. 2 on which to draw), to what other circuit element(s) the bulb is most similar (wire, battery, resistor, capacitor), what experiences lead them to choose their answer, and to define in their own words what is meant by a complete circuit.

Activity 1: Getting Hot is intended to help students better understand how the light bulb functions via a comparison with another well-known device, the heating element from an electric stove. Students are led through a series of focused questions to
determine how a light bulb filament and the heating element from an electric stove are similar and dissimilar to one another. Students also determine the number of connections each has, and whether or not the orientation of the connections to the battery is important.

Activity 2: That Glowing Feeling tests their idea of a complete circuit and confronts the idea that, although three circuits may physically appear to be identical, their actual operation may not. Students problem solve to find out why two out of three identical looking circuits do not function. The circuits are shown in Fig. 3 as they first appear to the students. Circuit 1 in Fig. 3 will result in the bulb lighting after the final connection is made. In the other two circuits, the light bulb does not light after making the final connection. In Fig. 3 (Circuit 2), the bulb is not fully screwed into the socket creating a break in the circuit. In Fig. 3 (Circuit 3), the batteries have been hooked together so that the negative poles are in contact with each other. Prior to making the final connection, students are asked if the circuits are complete based on their definition from the Bright Ideas exploration activity. They make the final connection and are again asked if the circuits are complete. If they answer that the circuit is not complete, then the students are asked to problem solve as to why the bulb would not light, fix the problem, and explain how this situation initially resulted in an incomplete circuit.

Insert Figure 3 here
Activity 3: Getting Connected directly confronts students’ alternative image of how a light bulb is internally wired. Its goal is to make a Christmas tree bulb light using a 6-V lantern battery connected to a large household socket (see Fig. 4). Students do this by first exploring how the socket works. Students record all their attempts to make the Christmas tree bulb light and note at what points on the socket they had tried. Near the end of this activity, they are given a battery, a wire, and a bulb and asked to make the bulb light given their new understanding of the internal wiring of a light bulb.

The application activity, Lighting Up the Night, provides students a chance to test their understanding of a complete circuit and their newfound knowledge of the internal wiring of a light bulb. Students are given a flashlight, two batteries, and some wires (see Fig. 5). They are asked to light the bulb without using the yellow casing. The casing is provided to the students for them to reference.

Field-testing the activities

The activities have been used with three different populations of students: high school physics (N = 13), and two introductory level university groups - algebra-based general physics (N=29), and conceptually-based physics (N=12). Both of the university
groups were enrolled in summer school. All students had already begun their study of electric circuits. The qualitative nature of the activities was unusual for all three groups. The high school students typically performed few hands-on laboratory experiments, but were shown many demonstrations in class. The most recent set of demonstrations dealt with electricity and was demonstrated in part via a Van de Graaff generator. Having seen what electricity could do via these demonstrations, the high school students were reluctant to initially touch and interact with the equipment. The university students were accustomed to quantitative laboratory activities that required numerous calculations and were more self-paced.

The students began by answering the questions in the Bright Ideas activity. We recommend having students independently answer the questions from Bright Ideas in the classroom so that their own ideas are elicited and not the ideas of someone else, or the textbook. For the field-test with the high school and general physics group, each of the authors was at a station (What a luxury!) to help guide and focus the students’ work, as well as to observe how the students interacted with the activities. Students were divided into three groups of 2-4 people. For the larger general physics class, we had 10 students per station subdivided into smaller groups of 3-4. Sufficient equipment was available for each group. Groups rotated between the three stations. The order of rotation did not matter. After all three stations had been completed we had a discussion that crystallized the main ideas from each of the activities. The main ideas were how a light bulb works, how it was connected within itself and to a socket, and what constituted a complete circuit. The final activity was Lighting Up the Night followed by a minute paper to reflect on what they had learned and pulled together from the activities. The minute
paper also served as an evaluation of the activities. The high school students had 40 minutes to complete the activities while the university groups had an hour and fifty minutes. Thus, there were difficulties completing all of the activities with the high school students. In the future, we recommend two class periods for those with 40-50 minute periods.

When the high school students were asked how they liked the activities most responded positively. The main complaint was lack of time to complete all the activities and to discuss the meaning of their results. One student remarked that there were not enough hands-on experiences in Activity 1: Getting Hot. Others did not see how Activity 1 was linked to the other two activities. We feel that this link, had time permitted, could have been established during the discussion phase. In Activity 2: That Glowing Feeling, some students in the high school and general physics groups believed that the light bulb was polarized so that a change in the wire connections would result in the bulb, not lighting. We believe that this is an artifact of overemphasizing the direction of current flow during instruction. We have hence added a section to Activity 1, which deals with the issue of whether a bulb is polarized or not. In Activity 2: That Glowing Feeling, students were not accustomed to unscrewed light bulbs and had difficulty seeing how this would affect the lighting of the bulb.

The university level students were split with their evaluation of the activities. Those who had an incorrect view of the internal wiring of a light bulb found the activities useful, often clearing up their confusion about how a light bulb functions and connects to a circuit. Those who had the correct view found the activities trivial. Both groups found parts of the activities to be repetitive. For this group of students, we recommend adapting
the activities and incorporating all or parts of them into an existing activity dealing with light bulbs and simple circuits.

For most students Activity 3: Getting Connected was the most illuminating. It was during this activity that students’ alternative image of the internal wiring of a light bulb was most strongly confronted. Many students began by trying to touch both leads from the Christmas tree bulb to the metal tab (indicated by the blue arrow in Fig. 6) of the socket. Students were visibly surprised when this did not work and proceeded to try other combinations. After several attempts, students found a combination that worked with little or no prompting. Students often found two screw (see green arrows in Fig. 6) connections on the bottom of the socket, which connected a metal strip on the base to the side of the socket, and would attempt to connect between them, which would result in the bulb lighting. They, however, did not realize that in the process they also made a connection to the metal tab, which actually completed the circuit. This was an important point that we had to emphasize to the students and encourage them to find other locations that would also work. However, one high school student lit the Christmas tree bulb in this manner, but refused to find other locations that also worked. As a result, this student believed that a light bulb connects only to the base of the socket and did not acquire the correct view that it is connected to the base and the side. Had time permitted, we would
have liked to have given this student the one wire task to complete, and to question how those results and the results from the socket related to one another. However, almost all of the students were able to quickly transfer their new knowledge of how the socket connects to a bulb to correct their image of a light bulb’s internal wiring.

Summing It All Up

To summarize, prior research has suggested that students who cannot light a bulb given a single wire, a bulb, and a battery are not able to reason correctly regarding complete circuits. No study to date inquired into how students believe a light bulb is wired. Our research shows that over half of introductory general education physics students believe that the wires from the filament are connected to only the base of the bulb at the bottom. There appears to be a correlation with the level of the introductory physics course taken (conceptual, algebra, calculus). The reason for this relationship is unclear from our current work, although it may have to do with students’ prior experience with light bulbs. Further research would need to be done to uncover the factors influencing this apparent correlation. We have proposed three activities that appear to aid students in developing the correct model of how a light bulb is wired. We recommend their use in high schools and as supplementary activities in the university. We also propose a definition of a complete circuit that classifies a short circuit as a complete circuit, but one that is not advantageous.

Acknowledgements
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Table I: Results from question asking where the wires connect to the “invisible” portion of a light bulb

<table>
<thead>
<tr>
<th>Class</th>
<th>Both wires to the bottom</th>
<th>Both wires to the side</th>
<th>One wire to the bottom, one wire to the side</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculus-based</td>
<td>18%</td>
<td>5%</td>
<td>72%</td>
<td>6%</td>
</tr>
<tr>
<td>Algebra-based</td>
<td>58%</td>
<td>9%</td>
<td>25%</td>
<td>8%</td>
</tr>
<tr>
<td>Conceptual-based</td>
<td>70%</td>
<td>0%</td>
<td>30%</td>
<td>0%</td>
</tr>
</tbody>
</table>
Figure 1: Typical drawings given by students while trying to make a light bulb light.
Figure 2: Diagram given to students to answer the question, “On the figure of the light bulb, draw in where you believe the two wires that come from the filament connect to the base of the bulb.”
Figure 3: Circuits for Activity 2: *That Glowing Feeling*. 

Circuit 1: 
Bulb lights

Circuit 2: 
Bulb does not light. 
Light bulb is unscrewed.

Circuit 3: 
Bulb does not light. 
Batteries are connected so that negative poles are in contact.
Figure 4: Equipment used in Activity 3: Getting Connected.
Figure 5: Equipment given to students for the application activity, Lighting up the night. Students were not allowed to use the yellow body of the flashlight, although it was given for them to reference.
Figure 6: Socket similar to those used for Activity 3: Getting Connected. The green arrows indicate the locations of the point where the base is connected to the side. The large blue arrow indicates the tab on the base where many students tried to connect both wires from the Christmas tree light.

3 Ibid, p. 17.
5 These activities are available by contacting the authors.

Students’ mental models of Newton’s second law: mechanics to electromagnetism
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Abstract

We investigated students’ mental models of Newton’s second law in various contexts encountered in mechanics, and for the first time, in electricity and magnetism. We interviewed a cohort group of 16 students enrolled in a two-semester calculus-based sequence of physics courses. We find that there are two predominant mental models: the “F = ma” or Newtonian model and the alternative “F = mv”, often called the Aristotelian model. Our results indicate that although the contexts may change, no new mental models emerge over two-semesters of physics instruction. However, we do find that some students, who may have adopted a Newtonian model after instruction in Newton’s laws during the early part of the first semester, may revert back to using an Aristotelian model when they encounter unfamiliar contexts. Our research also provides some insight into how students transfer their understanding of Newton’s second law from contexts in mechanics, where the law is first introduced, to contexts in electricity and magnetism where Newton’s laws are typically not explicitly addressed.

Relevant Previous Research

Mental models

Researchers have been probing students’ internal knowledge structures to better understand the origin of student difficulties. There is little agreement on the theoretical framework used to define and describe the underlying knowledge structures that students use. Driver (Driver, 1995) and others describe students’ mental models as ways in which learners organize experiences to minimize the mental energy needed to make sense of the world around them. Learners often test the adequacy of these models in the light of new experiences, thereby constantly modifying and reorganizing them. During instruction, students build on and modify these mental models. DiSessa’s (DiSessa, 1988) theoretical framework involves “knowledge in pieces” or “phenomenological primitives” or “p-prims.” Unlike a mental model, a p-prim can be either right or wrong, depending upon the context in which it is activated. Unlike the more holistic cognitive structures described above, that may be inconsistent with those of experts; p-prims have merely to be correctly activated. We found that our interview data was more amenable to a holistic mental model framework described above.

Students’ views in mechanics

Students’ ways of making sense of the mechanical world have been the object of much research. McCloskey (McCloskey, 1983) has pointed out that most students’ conceptions of motion are primarily based on their everyday experiences. Often these conceptions are rather well developed and deeply entrenched. Osborne (Osborne, 1984) found that most students are seldom consciously aware of these conceptions, although they may be using them in their everyday life. Researchers have found that the notion that “motion implies a force” is the most prevalent view among students. Some researchers (Halloun & Hestenes, 1985) (including us) have categorized this belief as Aristotelian, while others refer to it as the “impetus theory.”

Our research however goes beyond investigating students’ alternative views about motion. Rather, we have probed the extent to which students’ apply their views consistently across various contexts encountered over a sequence of two physics courses addressing concepts in mechanics as well as electricity and magnetism – conceptual areas that are not typically associated with the application of Newton’s laws. It is the first time that this kind of research is done in electricity and magnetism contexts.

Research Goals & Methodology

The overarching goal of our research is to develop a multiple-choice instrument – a ‘model inventory’ that allows educators and researchers to probe the mental model states of large numbers of students in a variety of contexts. To develop such an instrument, we began by exploring the knowledge structures that
students use in these contexts through in-depth interviews. We interviewed a cohort group of 16 students in a calculus-based physics class six times over the two-semester course sequence. The class operates in a ‘Studio’ format with two one-hour lectures and two two-hour labs integrated with the recitation. With the results from the interviews we developed a short (3-4 questions) multiple choice test, per each one of the contexts explored, that was applied to the entire section, N=240 students. We proceeded in two phases: Phase I during the first semester when mechanics was covered, and Phase II during the second semester when electricity and magnetism were covered. The first interview in Phase I was conducted before Newton’s Laws were introduced in class.

**Phase I (Mechanics): Research Instruments & Findings**

*Research Instruments*

For the first semester the interview protocol was partly based on questions from the Force Concept Inventory (FCI) (Hestenes, et. al., 1992). Interview 1 addressed two contexts pertaining to linear motion. These contexts, we believed had the fewest confounding variables. We label these contexts “vertical” and “horizontal.” The questions for each context that were posed to the students were designed specifically to elicit the mental model (Newtonian or Aristotelian) that students were using. The vertical context is based on the FCI question # 17: *An elevator is being lifted up an elevator shaft at constant speed by a steel cable.*

The horizontal context questions (Fig.1) were based on the FCI questions # 25-27: *A woman exerts a constant horizontal force on a large box. As a result, the box moves across a horizontal floor at a constant speed.*

- How does her force compare with friction?
- What force does she need to double the velocity?
- What force is needed to steadily increase the velocity?
- How will the velocity change if her force is doubled?
- What force is needed for 2 boxes with the same velocity?
- What happens if she stopped pushing?

In Interview 2 we explored the same vertical and horizontal contexts with other physical features, i.e. changing from pushing to pulling and from lifting to hauling. We also changed from a person to a mechanical device performing these activities. In Interview 3 we explored contexts that included Atwood’s machines. McDermott (McDermott, 1984) and others have demonstrated that these contexts pose special difficulties to students. The questions asked were similar to those in Interviews 1 and 2. We also asked students to predict the motion of each block when the strings connecting each of these blocks snapped.

*Research Findings*

We found two dominant mental models, Newtonian and Aristotelian, consistent with those reported in literature (Gabel, 1994). When students use both models to answer different questions in a given context, we say they are in a mixed model state. There is a significant increase in the number of students that consistently use the Newtonian model in Interview 2 compared to Interview 1 (Fig. 2). This is expected due to explicit instruction in Newton’s laws in the interim. In Interview 3 we find that students still use the two models. However, a few students who revert back to a previous model or to the mixed model state. Thereby indicating that student mental models induced due to instruction are stable neither with time nor with context.
With these results we developed four multiple-choice surveys, each pertaining to a different context used in to the interview protocol. The surveys were administered to the entire class (N=240). In particular, the surveys on the “horizontal” and “vertical” contexts were administered before and after instruction on Newton’s Laws. For the pre-instruction survey covering the “horizontal” context, 13% of the students used the Newtonian model in all questions. In the “vertical” context 21% used the Newtonian model in all questions. 36% of the students used the Aristotelian model in the “horizontal” context and 27% used it in the “vertical” context. After instruction the percentages changed to 37% and 42% of the students using the Newtonian model respectively for each context. The percentages using the Aristotelian model decreased to 16% and 5%, respectively for each context. All other students chose responses that were consistent with the Newtonian model in some contexts and the Aristotelian model in other contexts. We say these students are in a mixed model state. The other two surveys were administered after instruction on Atwood’s machines. An overwhelming majority (69%) of the students gave responses consistent with being in the mixed model state. The percentage of students using the Newtonian model consistently was down to 30%, and percentage of students using the Aristotelian model was negligible (1%). The overwhelming number of students in the mixed model state indicates that the Atwood’s machine context presents significant difficulties to students, as noted by other researchers (McDermott, 1984).

Phase II (Electricity and Magnetism): Research Instruments & Findings

Research Instruments

Most of the 240 students who were in the first semester (mechanics) course, were enrolled in the second semester (electricity & magnetism) course. We adapted questions from the Conceptual Survey in Electricity and Magnetism (Maloney, et. al., 2001) (CSEM). Our first interview included two mechanics contexts: pushing a box and a box sliding on an inclined plane. These contexts were intended to serve as a baseline, since they were similar to other contexts that followed, except that the origin of the force was mechanical rather than electrostatic. The first electrical context was based on CSEM question # 10 (Fig. 3): A positively charged sphere is released from rest in a region with a uniform electric field.

- Describe the force(s) acting on the charged sphere.
- Does the motion of the sphere change if the magnitude of the E field is doubled?
- Describe how the motion of the sphere would change if the: i) charge of the sphere suddenly doubles, ii) electric field suddenly doubles in magnitude? iii) electric field suddenly reverses direction? iv) electric field is suddenly turned off?

In the second context a positively charged sphere moving at a constant speed in a uniform electric field. The same questions as above were asked in this context.

In Interview 2 we explored the contexts of magnetic fields. The first context in the second interview is based on CSEM question # 21. Other questions described a charged sphere, initially in motion, moving toward a magnetic field region: In Interview 3 we explored electromagnetic induction in contexts similar to those found in textbook problems. One of the questions was a loop is being pulled out at constant speed of a region with a uniform magnetic field into the page.

Research Findings

Our results for the interviews (Fig. 4) show that the students use the same two dominant mental models (Newtonian and Aristotelian) as they did in the mechanics contexts. Observe that unlike in the very Interview 2 (Fig. 2), now nine of the students use the Newtonian model. By Interview 2, the use of
equations becomes important, so students differentiate between an electric and a magnetic field while applying Newton’s II Law. This makes sense since these concepts are abstract and students seem to rely more on the equations. In Interview 3, we find that Newtonian and Aristotelian models remain. However, none of the students are purely Aristotelian. We also observe that some students whose responses were consistent with the Newtonian model are now in a mixed model state.

Based on these results we developed thee multiple-choice surveys, each pertaining a different context from the interviews. Each test was administered to the entire class. The percentages of students who used the Newtonian model on the electric, magnetic and induction contexts is, 14%, 25% and 3%, respectively. As in the interviews, the percentage goes up on the second survey but it dramatically goes down on the third survey. The students who used the Aristotelian model are correspondingly 3%, 3% and 0%. Thus, it appears that the students “loose” their Newtonian ideas, but not completely because by the third test 97% of them used a mixed model. These results can also be due to the inherent difficulty of the concepts. Topics such as electromagnetic induction are typically considered to be quite difficult.

Conclusions

We found that students use two principal mental models (Newtonian and Aristotelian) spanning the topical areas of mechanics, electricity and magnetism. Some students might use conceptions from both models depending upon the context i.e. they are in a “mixed” model state. As expected, students became more Newtonian in their thinking with instruction but their Newtonian conceptions were not stable through various contexts. We found that most students were able to transfer their Newtonian models from mechanics to electrostatics and magnetism contexts, however some students reverted from a purely Newtonian state to a mixed model state in contexts pertaining to electromagnetic induction. Thus, students do use Newton’s second law throughout the two semesters of an introductory physics course, however because of the lack of familiarity with some contexts, it seems that their Newtonian conceptions are not stable. We believe that to alleviate this situation we should emphasize the connections to Newton’s laws in the second semester, when the students are studying electricity and magnetism, and the use of Newton’s Laws may have been forgotten. Making this connection as explicit as possible might enable students to see how Newton’s Laws apply in electricity and magnetism.

Acknowledgments

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References

Abstract

The everyday meaning and usage of several words can differ significantly from their meaning and usage in physics. Examining these differences, and how students respond to them, may shed some light on students’ physics learning difficulties. We surveyed (N=154) students in a conceptual physics course on their use of some words, “force”, “momentum” and “impulse.” We also interviewed some (N=14) of these students to probe their understanding of these terms and to triangulate data collected from the surveys. We found that students who were able to clearly discern the similarities and dissimilarities between the physics and everyday usage scored higher on a class exam that tested these concepts. In the interviews, students who were able to explain the distinction between the physics and everyday meanings often described the words in terms of the physical parameters associated with them.

Introduction

The vocabulary of science includes words that we often use in everyday contexts. When we learn science we are often introduced to new and sometimes contradictory meanings of these words. Research (Sternberg, 2001) has shown that we typically learn words in the context of objects and situations. Students bring these associations with them and may misunderstand the words when they are introduced in a physics class. Some researchers (Arons, 1997; Clerk, 2000; Palmer, 1997; Redish, 1994; Gilliespie, 2001) classify this confusion as a misconception.

Researchers have studied semantics in physics (Touger, 2000; Williams, 1999, 2000) and meanings of words (Touger, 1991; Styer, 2000; Hart, 2002). However, the problem goes beyond semantics (Touger, 2000). The linguistic relativity hypothesis by Sapir and Whorf (Sternberg, 2001) states that “we see, hear and otherwise experience very largely as we do because the language habits of our community predispose certain choices of interpretation”. An upshot of this hypothesis is that although language may not determine thought, it certainly may influence thought. Most research (Touger, 1991, 2000; Williams, 1999, 2000; Styer, 2000; Hart, 2002) has not discussed this relationship closely. This study will address that relationship.

In this paper, we address the question: Do the differences in the use of words between everyday life and physics inhibit learning of physics? We focus on three words that are common in any introductory physics course: “force”, “momentum” and “impulse”. We surveyed and interviewed students in a conceptual physics class at Kansas State University. Our findings enable us to suggest strategies that help students incorporate the physics meaning of these words into their vocabulary.

Research Goals & Methodology

Our goal was to study how students perceive the similarities and differences between the everyday meanings and physics meanings of the words and whether these perceptions affect conceptual learning in physics. Our research subjects were 154 non-science majors in a conceptual physics course. About 57% of the students had previously taken a physics course. Our research was conducted in three phases: pre-survey, post-survey, and an interview.

The pre-survey was administered before the relevant physics terminology was introduced. We asked students to construct three different sentences using the word (or its variant). Thus, the pre-survey told us how the students use the word in their everyday vocabulary. We categorized the sentences based on the usage of the word: Animate Verb, used as a verb associated with a person or animal; Inanimate Verb, used as a verb associated with an inanimate object; Noun; and Adjective or Adverb when describing an object or action.

The post-survey was administered after the term was introduced in class. We presented four sentences to the students each containing the word (or its variant). These sentences were selected from
among those written by students on the pre-survey. We asked students to explain the similarities and dissimilarities between the words used in each sentence, and their physics usage.

The post-survey results were classified into three categories: Category 1 includes students who can explain how the word “force” in each sentence, is both similar and dissimilar to the word “force” in physics; Category 2 includes students who are able to describe these similarities and differences for only a few of the given sentences; and Category 3 includes students whose responses indicate they cannot explain these similarities and differences for any of the given sentences. The validation of the categorization was done by an independent researcher who did the categorizing of the sentences independently. The validity was found to be 83%. Immediately after the post-survey the instructor administered a scheduled class test covering the topic of force. For our analysis we focused on the score for the questions relevant only to force, nine out of a total of 26. The questions were multiple-choice, only 2 of them required numerical calculations; the other seven questions were conceptual. These conceptual questions were similar to the ones in the Force Concept Inventory (FCI) (Hestenes, 1992).

We triangulated our survey data by interviewing 14 students toward the end of the course. The goal of the interview was to probe student understanding and use of these terms. The interview protocol was based on questions on the written surveys.

Research Findings

The word “force”

59% of sentences on the pre-survey included the word “force” as a verb. This data is consistent with the fact that the word “force” is most often used as a verb in everyday language (Styer, 2000; Hart 2002). 36% of the students in the second survey were in categories 1 and 2, i.e. they described the similarities and differences between the meaning of the word “force” in the given sentences and its physics meaning. The remaining 64% of the students, category 3, were not able to differentiate between the everyday and the physics meaning of the word force. Comparison of test scores for each category, shows that students who can identify and explain the physics meaning of the word “force” obtain higher test scores, thereby establishing a link between the linguistic ability of students and conceptual understanding, as measured by the test.

Our 14 interviewees included representatives from each of the three categories. In the interviews the students first wrote two sentences using the word “force” (or its derivative). They were asked to describe whether the word “force” as used in their sentences was similar or dissimilar from its physics usage. All of the interviewees were able make this distinction. When asked to explain why the word had a physics meaning almost all stated that the word relates to “pushing”, “pulling” or “motion”. When asked to explain why the word had an everyday meaning, they said it has to do with “mental power”, “following rules”, but “not in any physical sense”. Their explanation for the physics meaning is consistent with what they were taught in class: that force is “any influence that tends to accelerate an object; a push or a pull”. They also were taught that force equals mass times acceleration. Only 2 out of the 14 students were able to relate force to the mass of the object and/or its acceleration. In the everyday vocabulary “force” is not related to these terms, therefore the students do not use them. This finding supports the Sapir-Whorf (Sternberg, 2001) hypothesis.

In the second part of the interview the students were given four sentences and again asked to identify the meaning of the word “force” in each sentence. Again, all students were able to identify whether the meaning corresponded to everyday life or to physics because they focused on the context of the sentence. However, only two of the 14 students were able to explain how the meaning of the word is similar and/or dissimilar to its meaning in physics. These two students were also the only ones who associated force with mass and acceleration. For example when a student was asked to explain the meaning of the word force in physics she said “Force is weight, force of a book onto a table; force of a person while pushing a chair across the room.” When this same student was asked to explain the meaning of the word force in the sentence “The bulldozer forced the rock into the ditch,” she said, “the bulldozer has direct contact onto [sic] the rock, pushes the rock.” She identified force as a push, from the definition of force. Another student stated that, “Force causes movement, there are forces everywhere, like friction. Force is
mass times acceleration.” When this student was asked to explain the meaning of the word force in the bulldozer sentence he/she said “the bulldozer moves the rock into place, there is mass and acceleration.” The latter student is using the physical variables involved in force to explain why the word force in the sentence has a physics meaning. Thus, those students that relate the word to physical variables are more likely to explain the meaning of the word in physics.

The words “momentum” and “impulse”

Momentum and impulse were discussed in class, after the topic of force. 80% of the students’ sentences used the words as nouns in the pre-survey. Again, this is consistent with the most common usage of these words in everyday language. 36% of the students from categories 1 and 2 of the post-survey were able to explain how the words in the sentences provided were both similar and dissimilar to the words as used in physics. Students in category 1 scored higher on the test than students in categories 2 and 3. These results are similar to results for the word “force,” therefore reinforcing the link between the linguistic ability and conceptual understanding.

In the interviews we asked students to write two sentences each using the word “momentum” and “impulse.” 12 students interpreted the meaning of the word “momentum” in the physics context. However, only 6 of them related momentum to mass and or velocity. When asked to explain the physics meaning of “momentum”, typical responses included terms such as the “mass of the object”, “speed”, “action”, “motion” or “build up of energy”. When asked to explain the everyday meaning of “momentum” typical responses included “feelings”, “mental action”, “not necessarily physical motion”. It is interesting to note that momentum has a Latin root which means “movement”. The everyday meaning of the term is quite similar its physics meaning. It appears that due to this similarity, students are more likely to be able to explain the physics meaning of the term. For instance, when asked to explain the meaning of the term momentum, one student said, “When someone is running, he has mass and speed, he is creating momentum.” Another said, “Momentum is, ... as something falls speeds up... gains speed, gains momentum.” Only one of the 14 students was able to explain the physics meaning of the term “impulse”. The explanations of all of the other students corresponded to the everyday meaning of the term -- “instant action”, “spontaneity”, “something you do without thinking”. The dictionary meaning of the word impulse is “a sudden spontaneous inclination or incitement to some usually unpromoted action”. This meaning of the word is deeply embedded in students’ minds and it is difficult for them to relate it to physics. In fact the physics meaning of the term --, the magnitude of a force multiplied by the duration for which it acts, is quite different from the everyday meaning. In fact, the two meanings are almost contradictory. In everyday language, an impulsive action is associated with a short time duration, while in physics the longer the time duration, the greater the impulse. It appears that this difference makes it difficult for students to understand its physics meaning. Both students who correctly relate “momentum” to its physics meaning are unable to do so for “impulse.” Overall, the word “momentum” seems more intuitive to the students than the word “impulse”, because everyday and physics meanings of the word are quite different from each other. The Sapir-Whorf hypothesis seems to be applicable here. The everyday meaning of these words poses a barrier to understanding and assimilating the word in their physics vocabulary.

Conclusions

We surveyed 154 non-science majors in a conceptual physics class to study their perceptions of the similarities between the everyday and physics meanings of three commonly used words. Our findings show that students who can differentiate between the everyday and physics meanings of the words, and can explain the physics meaning, are more likely to obtain higher test scores.

Findings from our interviews indicate that students who are able to identify or remember physical variables related to the word are more likely to explain its physics meaning. Our findings also indicated that some words (e.g. “momentum”) seems more intuitive to the students, in that they always relate it to motion, and therefore are more easily able to understand and assimilate this word in their physics vocabulary. Other words (e.g. “impulse”) that have an everyday meaning different from their physics
meaning, are harder to understand and assimilate. Our findings are consistent with the Sapir-Whorf (Sternberg, 2001) hypothesis.

**Impact on Instruction**

Learning is often (Maloney, 1993) described as the acquisition of a different understanding of a concept that coexists and often competes with previous informal understanding. In this light, our findings indicate that physics instructors should be more cognizant of the use of language and the alternative meanings of physics terminology that their students bring with them to the class. We propose that comparing everyday and physics meanings of words will help students to assimilate the physics meaning of the word in their vocabulary. We do not believe the physics meaning of words will take the place of the everyday meaning but rather they would always coexist. Some instructors (McGuire, 2002) have suggested asking students to write essays using these words in different contexts. These different contexts would enable students to confront the very different use of these words in physics and everyday language. Many of the students in conceptual physics classes, such as humanities majors, have strong writing ability, and may find such writing tasks to be quite enjoyable. Efforts to inculcate superior writing skills across the curriculum have been used in several high schools and colleges. The writing exercises described above may have a unique role in such a curriculum.

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**References**

A framework for the dynamics of student reasoning in an interview
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Abstract

We propose a framework to characterize student reasoning during an interview. Our framework is based on data collected by five researchers with different goals. The research participants were enrolled in various physics courses at Kansas State University. Our framework has five elements: (1) External Inputs (e.g., questions, verbal, graphic and other cues) from the interviewer and interview environment; (2) Tools (e.g., memorized and familiar formulae, laws and definitions, prior experiences) that the student uses; (3) Workbench encompassing mental processes (e.g., induction, accommodation) that incorporate the aforementioned inputs and tools; (4) Answer given by the student and (5) reasoning paths connecting these elements. We have used a coding scheme to map out the reasoning paths in our framework. We discuss the applications and implications of our framework.

Introduction

Interviews have long been used in physics education research. However, they are often influenced by the researcher’s agenda and the assumption that knowledge remains static while it is probed. The latter is not always true. Sometimes students create answers as they speak; thus we need to be cognizant of the factors that may influence a student’s responses. This paper addresses the following questions:

- How do students construct their reasoning during an interview?
- What factors mediate students’ sense-making processes during an interview?

Relevant literature

Student knowledge has been described across a spectrum of grain size. Near one end of the spectrum, Driver (1995), Glaserfeld (1989) and others describe knowledge in terms of mental models. Learners test these models in light of new experiences, to modify or reorganize them. Near the other end of the spectrum, diSessa (1988) believes in knowledge in pieces or “p-prims”. Minstrell (1992) has divided concepts into units called “facets.” Hammer (2000) describes “resources” as the smallest usable pieces of knowledge. Our framework, which describes knowledge change in an interview is not anchored at any particular grain size, rather we consider all grain sizes equivalently.

Our framework describes knowledge change or cognitive dynamics in an interview. Piaget (1975) describes this change in terms of assimilation (adapting our experiences to fit our knowledge) and accommodation (modifying our knowledge to account for our experiences). More recently researchers have talked about conceptual change in terms of conceptual combination (Ward, 1997) or hybridization (Hrepic, 2002).

Researchers often use a flexible semi-structured interview format. This flexibility can make the format susceptible to a researcher’s bias. Recently, Scherr & Wittman (2002) demonstrated how a researcher’s agenda “filters” out some of what the student is saying in an interview. Our framework enables a researcher to look past and point to some of these “filters”.

Evolution of a framework

Researchers in the KSU physics education research group often shared anecdotal experiences of their interviewees making up or changing responses in an interview. Therefore we decided to re-examine our previous research data from the perspective of the dynamics of student reasoning in an interview. We emphasize that these data were from five researchers working independently on different projects with different goals. The students were from diverse backgrounds (non-science majors, engineering/physics majors) in different introductory physics courses. Through deliberations we identified four common elements that encapsulated the dynamics of reasoning in an interview.

Elements of the framework

Our framework is shown in Figure 1. The interconnecting arrows represent all possible reasoning paths followed by students as they articulate their response to an interviewer’s question.

External Inputs denoted by \{I\} is the input provided by the interviewer such as protocol questions, follow-up or clarification.
questions, hints or cues, both verbal and non-verbal. It also includes other materials e.g. text, pictures, demos, videos, etc. that the student is allowed to use.

**Tools** denoted by {T} include the knowledge structures that a student uses in her or his reasoning. Tools can be either pre-existing or created. Existing tools include a student’s prior experience, memorized information, facts, data, formulae, definitions, rules, procedures etc. It also includes knowledge structures of different grain sizes, ranging from p-prim to facets to mental models or theories. Created tools are dynamically constructed knowledge and experiences at an earlier instance in the interview, such as answers to previous questions or other knowledge etc. acquired through previous questions.

**Workbench** denoted by {W} includes mental processes used by the student. These processes activate dormant knowledge in {T}, such as executing a known rule or procedure. These processes often reorganize and restructure knowledge (e.g. assimilation, accommodation.) or synthesize different pieces of knowledge (e.g. conceptual combination, hybridization). {W} includes transferring and applying prior knowledge and experiences in new situations such as analogical, inductive or deductive reasoning as well as decision making. The latter can occur when a student decides that a given analogy or explanation is applicable to the situation at hand or when the student has to choose an answer from more than one option.

**Answers** denoted by {A} are the conclusion of a reasoning process, but could be articulated first by the student. Answers could also be an intermediate stopping point. This type of situation occurs during metacognition (Flavell, 1979). Answers can be decisive i.e. a single conclusion or indecisive, e.g. two or more answers, “don’t know” or a request for more information. In the latter case {A} is in fact a question.

**Some caveats**

The descriptions of various elements in our framework are not exhaustive e.g. {W} can include processes (e.g. abduction (Josephson, 1994)) that we have not mentioned. It is possible that a student’s statement cannot be uniquely categorized as a particular type of tool. For instance, a {T}, say prior experience (e.g. pushing a grocery cart), could also be a p-prim (motion implies force). Similarly in {W} two processes can be inseparable e.g. abduction includes decision making. The boundaries between various elements in our framework can often be difficult to distinguish. e.g. the procedure “If ‘X’ then ‘Y’” is either a {T} or a {W}. Elements can sometimes be implicit e.g. the answer {A} “It speeds up because a net force acts on it” implicitly uses {T}, Newton’s II law, without explicitly stating it.

We acknowledge that our framework, may not characterize a student’s reasoning definitively. In some instances, it is plausible that two researchers analyzing the same transcript using our framework may arrive at slightly different descriptions of a students’ reasoning path. Therefore our framework is susceptible to a researcher’s bias in ways similar to other methods of qualitative research analysis.

**An Application of the Framework – Analyzing Students’ Reasoning Paths**

Our framework can unearth some interesting reasoning paths used by students and their components. An example (Fig. 2) from our interview data demonstrates the details of cognitive conflict demonstrated by a student during an interview. Cognitive conflict or dissonance (Festinger, 1957) can help students learn science (Hewson, 1984). Piaget’s (Piaget, 1975) cognitive disequilibrium occurs during assimilation and accommodation (both {W}), when a learner’s internal knowledge {T} conflicts with her/his external experience in a discrepant event {I}.

When asked to predict how the brightness of two bulbs in parallel will compare to a single bulb {I1}, the student answers based on a p-prim (more is less) {T1}, and elaborates {W1} their answer - less bright {A1}. The interviewer completes the circuit so that the bulbs light and asks what happened {I2}. The student answers that they stayed the same {A2}, reasoning that the energy must be the same going to each bulb {W2t}. The tool, which is implicit, is denoted by ‘t’.

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**Fig. 2: Conflict resolution reasoning path**
Advantages of using the framework

The process of identifying various elements of the framework in an interview transcript forces a researcher to carefully consider what the student is saying, without overlooking words or phrases which may have been filtered out by the research agenda. The framework urges the researcher to look for evidence of each of these four elements. Therefore, using this framework alerts the researcher to the absence of one or more of these elements, especially \{T\} and \{W\}, thereby avoiding an exclusive focus on \{A\}. By interconnecting the elements, the researcher can carefully trace the effect of various inputs and cues. For instance, the \{T\} that a student uses when presented with a particular input \{I\}, may have been lost if the focus had been only on \{W\} or \{A\}.

The framework can help the researcher design questions that elicit cognitive tools \{T\} and processes \{W\}. During the interview, the framework can help the interviewer ask follow-up questions \{I\} that explicate students’ reasoning. The framework can also help the researcher glean overall trends in a student’s reasoning across several questions, or to analyze a transcript at multiple grain sizes. The example below shows a transcript analyzed at two grain sizes (Figure 3). We can use a broad brush to see global trends in the data and large grain size knowledge elements (e.g. mental models). We can also use a finer brush to see details that emerge from the data such as small grain size knowledge elements, (e.g. resources) or transfer, selection of various tools and the back and forth deciding between different answers.

Our framework can be applied in two ways. First, it can be used to understand what students say, by categorizing various words and phrases in the transcript as \{I\}, \{T\}, \{W\} or \{A\}. Second, it can be used to infer what students think. This mode of application is more susceptible to researcher interpretation and bias than the first one. In the example below (see Table 1), a student was asked to explain how sound propagates through a wall. By parsing the student’s response one can identify \{W\}, \{T\} and \{A\} as they chronologically occur in the transcript. A researcher can also infer that the student uses analogical reasoning (Gentner, 2000) involving three \{W\} processes: -- recognizing a target \{T\}, abstracting structural similarities between source and target, and mapping similarities from source to target. The first of these processes is somewhat evident in the transcript. The other two are inferred, based on our theoretical understanding of analogical reasoning. Therefore the reasoning path goes back to \{W\} (for abstracting and mapping) before terminating at \{A\}. Note, that there was no attempt made in the inferential analysis to separate the abstraction and mapping processes in \{W\}. This demonstrates that although the framework can bridge data with theory, use of the framework is ultimately grounded in the data.

Table 1: Applying the framework in different ways to...

<table>
<thead>
<tr>
<th>What the student says</th>
<th>What we infer the student thinks</th>
</tr>
</thead>
<tbody>
<tr>
<td>{I} Asked how sound gets to the other side of a wall.</td>
<td>Student recognizes {W} that the situation is analogous to a maze {T} for the sound. She applies the analogy to deduce {W} that air works its way through until it gets to other side of the wall {A}.</td>
</tr>
<tr>
<td>{W} “Well, I would say that to me it is somewhat like”</td>
<td></td>
</tr>
<tr>
<td>{T} “a maze for the sound”</td>
<td></td>
</tr>
<tr>
<td>{A} “it just kind of works its way through until it gets to the other side.”</td>
<td></td>
</tr>
</tbody>
</table>

Connections with cognitive psychology

It may be evident from the nomenclature of various elements that our framework uses the metaphor of a workshop. The input \{I\} is analogous to the work order given to a worker (e.g. build a chair). The tools \{T\} are
analogous to the tangible implements (e.g. saw) that the worker uses, as well as her/his skills in performing the task. The workbench \{W\} is analogous to the work area (e.g. work table) as well as the fabrication processes. The answer \{A\} provided by the student is analogous to the finished product (e.g. chair) constructed by the worker. Our framework also has underpinnings in cognitive psychology (Driscoll, 2000). The sensory input and response are analogous to \{I\} and \{A\} respectively. The short-term (working) memory and the mental processes occurring therein are analogous to \{W\}. The long-term memory and information stored therein are analogous to tools \{T\}. Our framework also shares commonalities with a metaphor in cognitive psychology – the computer. Input \{I\} is analogous to input devices (e.g. keyboard). Answer \{A\} is analogous to output devices (e.g. monitor). Tools \{T\} are analogous to stored information (data, software etc.) on the hard drive. Workbench \{W\} is analogous to active processes in a processor or RAM.

**Other Issues & Conclusion**

Our framework does not address other issues relevant to interviewing, such as a student’s emotional state while participating in the interview. Wittmann and Scherr (2002) have demonstrated that a student’s epistemological stance can mediate and constrain a researcher’s access to a student’s reasoning in an interview. A student’s epistemological beliefs may be characterized as tools \{T\} in our framework, but when we originally constructed our framework from our data, we neglected to include a student’s epistemological resources as \{T\}. This issue is worthy of further discussion as we continue to refine the framework. Nevertheless, applying our framework entails an attention to detail that can alert a researcher to statements that may reflect a student’s epistemological stance (e.g. “…because my teacher told me so”). Such statements may have gone unnoticed in the analysis.

In conclusion we believe that our framework, in spite of its limitations described above, provides a useful tool for gleaning the dynamics of student reasoning in an interview.

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**References**

DYNAMIC TRANSFER:
A PERSPECTIVE FROM PHYSICS EDUCATION RESEARCH

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Abstract

We focus on contemporary models of transfer of learning and contrast them with previous models in this area. We observe that paradigm shifts in studying transfer are similar to changes in perspectives adopted in physics education research. Therefore, research efforts in these two fields can productively complement each other. Based on contemporary views of transfer of learning, we have adapted our previously developed analytical framework to characterize transfer as it occurs dynamically in an interview. Our adapted analytical framework is also consistent with a theoretical framework proposed by Redish that addresses several cognitive and epistemological issues. In light of Redish’s framework and contemporary transfer models, we have demonstrated how our analytical framework can help identify and characterize transfer as it occurs in an interview. We describe instances in which students transfer their learning spontaneously in an interview as well as those in which transfer is promoted by scaffolding provided by the interviewer. In connection with the latter, we propose a relatively unused methodology – the teaching experiment (or interview) that can be a useful research tool in helping researchers learn more about how students dynamically transfer their learning from one context to another.