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 on 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?

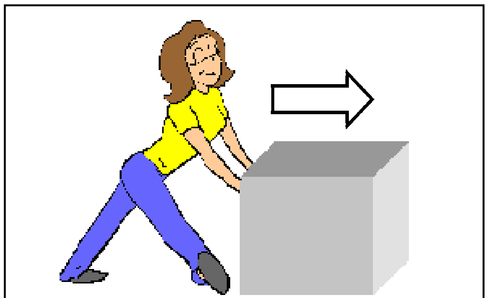

Fig. 1: The "horizontal" context adapted from FCI Q # 25-27.

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.

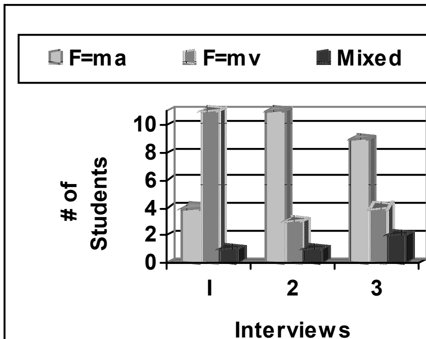

Fig. 2: Results for Phase I

With these results we developed four multiple-choice surveys, each pertairning 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 consitent 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 reserachers (McDermott, 1984).

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

<u>Research Instruments</u>

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.*

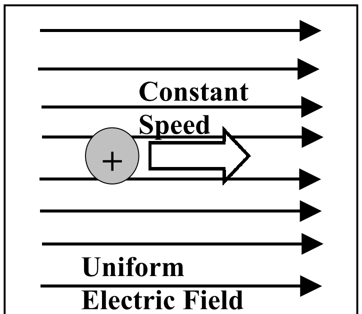

Fig. 3: Electric field context based on CSEM Q# 10

- 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.

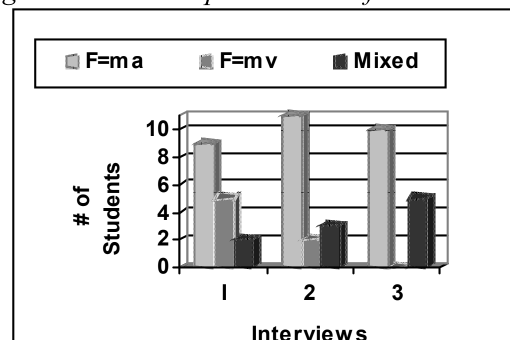

Fig. 4: Results for 2nd semester

<u>Research Findings</u>

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 pertairning 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 correpondingly 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

This research is supported in part by NSF grant # REC-0087788.

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