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Thinking Outside the Box: Understanding Students Thinking on Statics in Mechanics

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Thinking Outside the Box: Understanding Students Thinking on Statics in Mechanics (a work in progress)

Student-centered pedagogy requires instructors to engage deeply with student thinking, as opposed to didactically prescribing one correct problem-solving algorithm [1]. In this work, we explore student understanding of friction forces in the context of static equilibrium in a mechanics class, a course with which students often struggle [2]. To improve the learning experience of these students, we first had a large set of students (232) provide written explanations of their answers to a statics concept question. These responses were examined, sorted into helpful and unhelpful reasoning patterns, and coded into themes. To more deeply explore student reasoning patterns, we use a think aloud protocol to study how students address this same friction problem with multiple solution paths, and how they assess their own thinking. Specifically, we ask:

1. What patterns emerge in student approaches to the problem?
2. How do different student approaches interact with their assessment of their thinking?

Previous Work

Concept questions provide one avenue for educators to engage in student-centered pedagogy where the students influence the content, materials, and pace of learning by providing faculty feedback on current understanding of a topic [1]. Concept questions are typically multiple-choice questions with one correct answer and a few enticing distractors. Concept questions are often designed to have multiple solution paths to consider, and ask students to provide a justification and confidence level for their answer. Collecting justifications provides further insight into correct or incorrect answers. For instance, a correct answer might have an incorrect justification and an incorrect answer might indicate some level of conceptual understanding—both provide an opportunity for faculty to better understand students' current understanding of the concept [2]. For example, the friction equation $F = \mu N$ is not applicable in all cases. If a student implements this equation where it does not apply, instructors might recognize overzealous transfer, in which a helpful reasoning pattern is applied where it doesn't apply [3]. Implementing concept questions with justifications provides input on the pace and content of current or future lessons. Koretsky [4] found that providing a justification requirement to a question increased selection of a correct answer versus when no opportunity for justification was provided. Providing confidence level is another data point for faculty to gauge student understanding when reviewing student responses [5].

The Concept Warehouse (https://conceptwarehouse.tufts.edu/cw/CW.php) provides rapid deployment of concept questions through an online platform, originally developed for chemical engineering faculty. The Concept Warehouse has nearly 3,000 concept questions for implementation in or outside of class. Faculty can view responses in real time or after the question has closed. The Concept Warehouse has grown rapidly in use by students and faculty and been expanded to include mechanical engineering course concepts. An initial study [2] has assessed integration of Concept Warehouse at seven diverse institutions: a large research public university, a small private university, two 2-year colleges, a large non-PhD granting public university, a mid-sized public university, and a bilingual research university. Mechanics instructors at the seven diverse institutions implemented four common statics and four common dynamics concept questions. In this study, the box problem (Figure 1) was presented to 232 students. The answer selection, justification and confidence level were collected and a small sample of students were re-engaged for follow-up interviews.

You are holding a box of books with flat hands. If you press harder, what happens to the friction force applied by your hands onto the sides of the box?

It increases

It remains the same

It decreases

Not enough information to determine

Figure 1: The Box Problem (ConcepTest #4497)

The initial study found that in general, no more than one-third of students who selected correctly could justify their answer adequately [2], supporting a similar result observed in [4]. The study [2] found that female students report lower confidence levels in their answers than males, regardless of answer correctness. Papadopoulus concludes that studying student responses more deeply and analyzing "open-ended responses, both to better understand what students think, and to better understand the limitations of concept question results" is a next step in studying concept questions [2]. Our current study expands upon previous work using the same "box problem" by first analyzing 232 student responses, and then by introducing a think aloud protocol to better understand the thinking of students in the answers they provide.

Preliminary Results

To better understand student conceptions of friction and equilibrium, we examined the answer explanations of a large set of students (232) to the statics concept question shown in Figure 1. Of those students, 37% selected the correct answer that the friction force remains the same when you press harder, and, interestingly, those who answered incorrectly were more confident in their answer than those who answered correctly (4.12 *vs* 3.90 out of 5), though the difference was not statistically-significant ($p = .084$). We analyzed the students' explanations of their answers using thematic analysis. Student answers were analyzed as submitted and quotations below represent the responses exactly, without correction for spelling or grammar mistakes.

Three groups of students emerged. The first group (group 1) used physical reasoning to reach the correct answer. Most explained the balance of forces, for example:

> *"There is no increase to the downward force applied to the box, and the box is not at impending motion. The weight of the box stays the same and the frictional force due to the hands have to be equal and opposite to the weight. Therefore, the friction force does not increase."*

Some additional students explained the physical consequences if the friction force were to increase: "If the force of friction changed and the weight of the box did not, the forces would not be balanced and the box would accelerate."

The second group (group 2) also used physical reasoning, but leading to the wrong answer. For example, one student said, "when you are holding something and applying more force to the sides of it, the friction force will increase because it takes more force to get the object to move." This student is correct that with increasing normal force, the downward force necessary to move the box would increase; however, what is increasing in that case is the maximum friction, not the actual friction given that the box is not at impending motion. Another student said, "If you press harder their is a greater force holding the box from slipping so their is less friction force needed to keep it from slipping" – this student seems to think of the normal force and friction force are two different forces contributing to holding the box up, and thus that in balancing the downward force of gravity, if one force holding the box up (the normal force) increases, then the other (friction) decreases.

Finally, a third group (group 3) overzealously applied the friction equation, $F = \mu N$, which would only apply if the box were moving or at impending motion. For example, one student said, "the force of friction is directly proportional to the normal force and so the harder you push, the more normal force you have and therefore you have more friction." Many other students simply wrote out the equation when explaining their answer.

We classified 48 students as belonging to group 1, 28 to group 2, and 86 to group 3; the remaining 70 students gave explanations with insufficient length or detail to classify. Statistical analysis of these three groups showed that group 3 was the most confident (4.48 out of 5), followed by group 1 (4.19), and group 2 (3.82). Kruskal-Wallis analysis showed that student confidence was very significantly related to which type of explanation they gave between groups 2 and 3 ($p < .001$). We posit that students feel very confident applying the friction equation, and when they do so without realizing that they need to think more deeply about the question, they are very confident in their answer despite being wrong. Students who apply physical reasoning to reach the correct answer are less confident (though not statistically-significantly, $p = .21$), perhaps because they have noticed and grappled through the complexities of the problem and are aware of other possible solution paths. Finally, students who apply physical reasoning to reach an incorrect answer are least confident, because they did not rely on an equation that gave them false confidence, but also did not reach a logical explanation that they fully trusted.

In reviewing student responses, it was often difficult to code answer responses. The research team would have liked to ask students' follow-up questions to their justifications to better understand their reasoning. As a result, we developed a think aloud protocol to better understand student thinking and aid in accurate data analysis.

Think Aloud Protocol

A think aloud protocol asks students to verbalize their thoughts as they solve a problem to allow the research team to better understand how students are thinking. The think aloud protocol was used to document various solution paths taken by participants to solve the box problem (Figure 1). Think aloud interviews started with a practice problem to get the student familiar with the think aloud protocol, as it was likely many students' first time participating in this type of study. The practice question was also related to mechanics but focused on projectile motion. The interviewer conducted the practice question in the same manner as the box problem (Figure 1) and did not disclose that this question is for the purpose of practice. After students worked through the first problem, the interviewer presented the box problem. Students were asked to explain their line of reasoning, select their answer, and provide their confidence level in that answer. The interviewer asked follow-up questions based on their responses and asked if their confidence level or answer had changed after follow-up questioning. The interview audio and work of the student were recorded on an iPad and used as data along with interviewer notes.

Recruitment

Participants were students in a statics and deformable bodies course that elected to participate and were currently taking or had completed introductory physics. Students were recruited from a single instructor across three sections at the United States Air Force Academy and twenty-one interviews have been completed and 10 more are planned to be completed in the future. Interviews were conducted in accordance with an approved protocol and attainment of informed consent.

Think Aloud Results

For the purposes of this work-in-progress study, we report on the analysis of four student interviews of interest; future work will expand this analysis. The selected four students initially selected an incorrect answer and after follow-up questions, changed their answer to the correct choice. Initially, half the students (Students A and B) used the friction equation $F = \mu N$ to select an incorrect answer and the other half (Students C and D) used physical reasoning to select an incorrect answer. Follow-up questions varied based on individual solution paths. For example, if the interviewer had an indication an equation was used, they asked the student which, if any, equations were referenced. All students were asked to draw a free body diagram of the system after their initial answers.

Those who initially referenced an equation to solve the problem were faced with an inconsistency when drawing their free body diagram. The equation implied friction would increase but the free body diagram did not support that result if the mass of the box did not change. Figure 2 shows free body diagrams and interview quotes from both students who used an equation initially (Students A and B). Both students used adequate justifications to reach the correct conclusions, changing their answers, but use words such as “not sure” and “second guess myself,” indicating a lack of confidence and conflict.

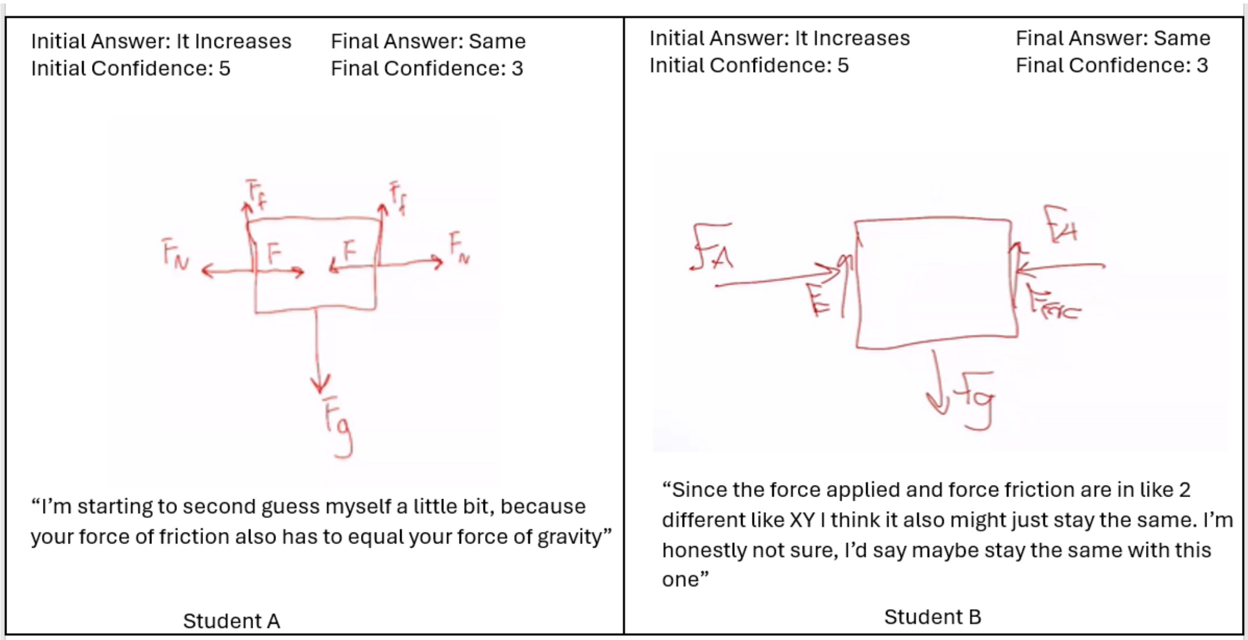

Figure 2: Student interview quotes and free body diagrams for the box question during follow-up questions. Both explanations correctly identify and justify their answer but indicate low confidence.

When comparing the confidence level of Students A and B referencing an equation only and using a free body diagram during follow-up, confidence levels decreased by two in both cases, even though both switched from an incorrect to a correct answer. Although this is a small sample size, it supports our hypothesis that students who use only equation-based reasoning are more confident because they have not considered the complexities introduced by physical reasoning; when the interviewer prompts them to think more physically using a free-body diagram, they do so correctly, but their confidence decreases.

The other two students, Students C and D, selected incorrect answers using physical reasoning, indicated by statements such as “the more I push in the more force it is going to have” and “when I'm thinking about friction, I'm really thinking about things like rubbing up against each other.” When prompted, they stated that no equations were used in their determination of an answer. Both students decided to change their answer when asked if the system was in equilibrium but came to the same answer for different reasons. Student C initially selected it increases, and their justification was that it was impossible to use identical forces from each hand, meaning that the system is not in equilibrium. Upon being asked to assume equilibrium, the student indicated it would have to remain the same due to the equilibrium condition, and changed their answer to it remains the same. Their confidence went from 4 to 3. Student D initially selected not enough information to determine, and their justification was it is needed to know if this system had motion or not. Upon being asked to assume equilibrium, they said no friction existed before and after an increased force is applied and changed their answer to it remains the same. Their confidence went from 2 to 3. Figure 3 shows free body diagrams and interview quotes from students C and D.

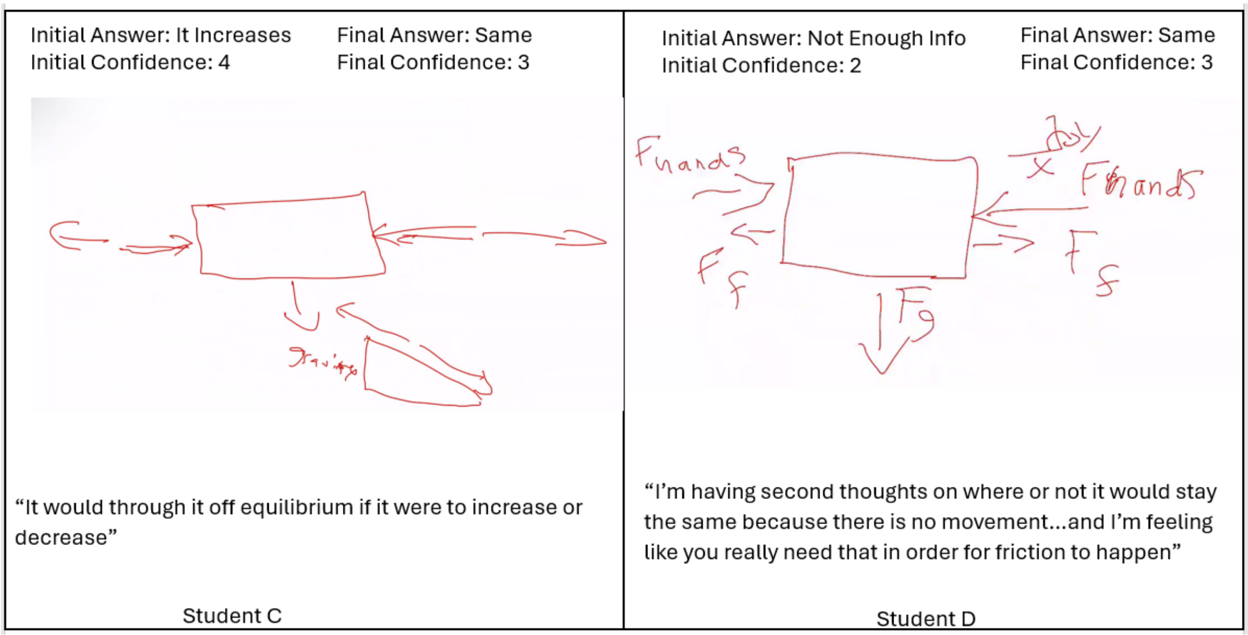

Figure 3: Student interview quotes and free body diagrams from the box question during follow up questions. Both explanations incorrectly identify friction as acting opposite to the applied force. Both students apply equilibrium to get to the correct answer. Student C applies equilibrium correctly while Student D applies equilibrium and associates absence of friction before and after more force is applied to the box.

Both students applied equilibrium to get a correct answer. Student C applied a correct connection between friction and equilibrium, although they did not correctly identify the direction of friction. Student D incorrectly associated friction and equilibrium, stating that no friction was present before or after increased force was applied to the box due to the system not moving. Although Student D had an incorrect justification, their confidence increased. Meanwhile, student C had a correct justification and confidence decreased. The researchers posit the students’ confidence went up despite an incorrect justification because this student selected “not enough information to determine” and was able to confirm the information needed to come to an answer. When the missing information was provided, this could have created an increased confidence in the selected answer. Figure 4 shows a solution flow diagram for these students.

Conclusions

A thematic analysis of student written explanations of their answers to the concept question shown in Figure 1 unveiled three groups: the first identified the correct answer using physical reasoning, the second identified an incorrect answer using physical reasoning, and the third chose an incorrect answer using a friction equation, $F = \mu N$. We conclude students feel very confident applying the friction equation, and they do so without realizing a need to think more deeply about the question. Interestingly, these students are very confident in their answer, despite being incorrect. Students who apply physical reasoning to reach the correct answer are less confident, perhaps because they have noticed and grappled through the complexities of the problem and are aware of other possible solution paths. Finally, students who apply physical reasoning to reach an incorrect answer are least confident, because they did not rely on an equation that gave them false confidence, but also did not reach a logical explanation they fully trust.

Thirty percent of analyzed student answers gave justifications with insufficient length or detail to classify, and even some students who were classified into one of the three groups may have used more complex reasoning than evidenced by their written responses. We designed a think aloud protocol to help faculty to better understand student thinking and increase the percentage of classifiable answers. The think aloud is intended to illuminate why students use a selected problem-solving method and their source of confidence in a given answer, as well as how their thinking changes when considering different factors and using different methods, such as drawing a free body diagram.

After completion and analysis of a small case of think aloud interviews, we found that students change their incorrect answer after follow-up questions to a correct answer but often decrease their confidence level. The students in this small sample fall neatly into the groups of students identified in the initial analysis: two students selected an incorrect answer using physical reasoning (group 2), and two students selected an incorrect answer using the friction equation (group 3) before follow-up questions. We hypothesize these students decreased their confidence after follow-up because students had to confront two concepts that, at the time, seem in conflict with each other. In the case of students A and B, students saw that the FBD did not agree with the equation and selected to trust the FBD and equilibrium analysis over the friction equation. However, their confidence decreased because they are now considering two answers that they find justifiable.

In future work, we plan to analyze 17 more think-aloud interviews that we have already conducted, and conduct and analyze 10 more. Based on that analysis, we plan to provide recommendations to faculty to improve the learning experiences of students through student-centered pedagogy in mechanics courses. In this small case study, researchers identified think aloud interviews to be educational in nature because it gave students an opportunity to reason through new problems out loud and answer follow up questions. This process allowed students to consider new ideas and solution paths and learn something in the process. Researchers posit a think aloud could be used to teach students either one-on-one or adapted in some way in the classroom environment.

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