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Unpacking Student Reasoning in Rigid Body Equilibrium: Insights from Think Aloud Protocols

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Student-centered pedagogy requires instructors to engage with student thinking instead of prescribing one correct problem-solving method [1]. In this work, student understanding of rigid body equilibrium is explored as a follow-on to previous work [2]. A think aloud protocol is used to study how students address a problem with multiple solution paths and how they assess their own thinking. Study participants are students in a combined statics and deformable bodies course that elect to participate and are currently taking or have completed introductory physics. The interview begins with a projectile motion practice problem to get the student comfortable with the interview process, followed by two questions of interest. The first is the box problem followed by the rigid body beam question. The rigid body beam question shows a simply supported T-beam (Figure 1) with an applied load. Students are asked to predict how the reaction forces at the pin support change if the moment arm of the applied load changes. They explain their reasoning using a think aloud protocol, select their answer, and provide their confidence level in that answer. The interviewer asks follow-up questions based off their responses to better understand their thinking and asks if their confidence level or answer has changed after follow-up questions. Responses are recorded on an iPad using audio and screen capture recording and analyzed for common themes.

This work focuses on the rigid body beam question. Thirteen interviewed students completed this question using a think aloud protocol. Initial analysis of student responses shows student confidence increases after follow-up questions, regardless of student answer correctness. This indicates that something about the process of think alouds relates to student confidence. In previous work, think alouds were observed to be educational in nature [2]. When reviewing explanations from students who selected incorrect answers, many students identified a pin to have a reaction moment and answered the question with regards to the magnitude and direction of a reaction *moment* at A instead of the resultant reaction *force*. Additionally, many students who answered incorrectly struggled with the concept of a resultant reaction force. Those who got the magnitude correct but had an incorrect direction used physical understanding such as the concept of leverage or equilibrium equations to identify an increase in magnitude resulting from the changed dimension. Researchers posit that students were able to get the magnitude but not the direction because students often struggle with visualizing force direction. By examining student reasoning patterns, instructors can develop more impactful pedagogical practices to target student difficulties.

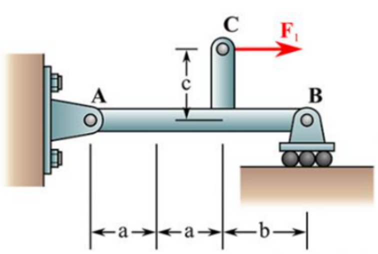
Previous Work

The Concept Warehouse (https://conceptwarehouse.tufts.edu/cw/CW.php) is a faculty resource to rapidly deploy concept questions through an online format. The Concept Warehouse has ~3,000 concept questions for use in or out of class in a variety of topics, including mechanical engineering concepts. The concept questions from this resource have been studied by many [3-5] and is the focus of this work.

Concept questions are typically multiple-choice questions without calculations. They can be used to see how well students understand underlying scientific and engineering principles, rather than how well they can search for the right equations. The Concept Warehouse has options to ask students to justify their answer with an explanation box to collect answer reasoning and require students to select a confidence level in their answer. Answer justifications can provide interesting insights into student understanding because correct answers do not always correspond with correct justifications or helpful reasoning patterns. Additionally, incorrect answer justifications might indicate some level of conceptual understanding [3]. Both provide good data points to instructors to tailor the pace and examples used in class to improve concept understanding. Koretsky [6] found that requiring a justification to a question increased selection of a correct answer versus not requiring justification.

The research team investigated concept questions to better understand student thinking of mechanics concepts. 232 student responses for "The Box Question" (ConcepTest #4497) were collected and analyzed for similar themes. Three groups emerged: group 1 used physical reasoning to achieve a correct answer, group two used physical reasoning to get an incorrect answer, and group three overzealously applied the friction equation $F = \mu N$. Group 1 had 48 students, group 2 had 28 students, group 3 had 86, and 70 students were not classified due to insufficient detail or length. In response to the 70 students who could not be matched to a category, a think aloud protocol was proposed to better understand student thinking. During student interviews, an initial question served as a practice, although not disclosed to the student, followed by the box question. At random, 13 of the 46 students were asked a rigid body beam question (ConcepTest #4660), the focus of this study. Students who answered the rigid body beam question followed the same protocol as the study in [2] and were from the same pool of recruitment.

The object is supported by a pin at A and a roller at B. How will the resultant reaction force at A change if the dimension c increases? Assume the magnitude of F_1 does not change.



The magnitude will increase, but the direction will stay the same.

The magnitude will be unchanged, but the direction will change such that the angle (measured CCW) between the force at A and line AB decreases.

The magnitude will be unchanged, but the direction will change such that the angle (measured CCW) between the force at A and line AB increases.

The magnitude will increase, and the direction will change such that the angle (measured CCW) between the force at A and line AB decreases.

The magnitude will increase, and the direction will change such that the angle (measured CCW) between the force at A and line AB increases.

Figure 1: The question of interest, "the rigid body beam" question (ConcepTest #4660)

Think Aloud Protocol

Thirteen students were asked the rigid body beam question (Figure 1). The correct answer to this concept question is the last answer option: "The magnitude will increase, and the direction will change such that the angle (measured CCW) between the force at A and line AB increases." The research team is interested if the student will draw a free body diagram and elect to sum moments about either point A or B to determine their answer. When looking at equations of equilibrium, students should recognize the applied moment about both A and B due to F_1 will increase. If they sum moments about A, that means the upward vertical reaction at B will increase - and therefore the downward vertical reaction at A will also increase in magnitude. Students should identify A_x does not change as dimension *c* increases. Using knowledge of the resultant force magnitude and direction from the Pythagorean theorem (Equation 1 and Equation 2), it can be reasoned that the resultant reaction force at A would increase as would the angle since Ay increases.

Equation 1: $$R = \sqrt{{A_x}^2 + {A_y}^2}$$

Equation 2: $$\theta° = tan^{-1}(\frac{A_y}{A_x})$$

Students were asked to implement a think aloud protocol when answering concept questions. A think aloud protocol asks students to verbalize their thought process while solving a problem, allowing researchers to gain insight into student thinking. This protocol was used to document the various solution strategies employed by participants in solving the question of interest (Figure 1).

The think aloud sessions began with a practice problem to help students become familiar with the process (Figure 2), as many likely never participated in this type of study.

A cannon ball is shot off the side of a hill, the projectile motion path looks most like which path?

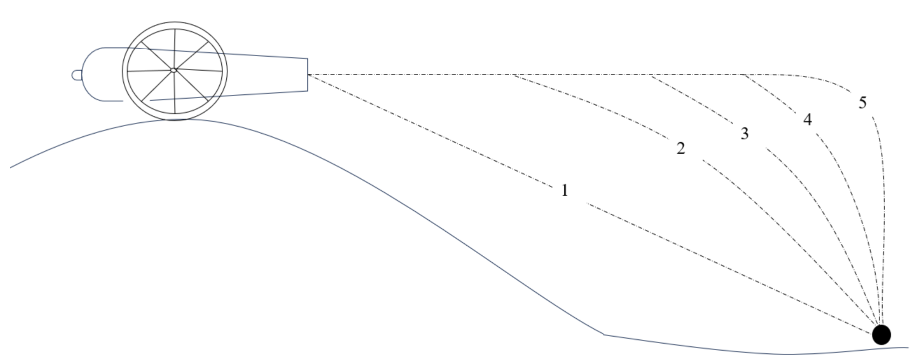


Figure 2: The practice question for students to practice thinking out loud and understand the protocol [7]

After students completed the initial problem, the interviewer introduced the box question (Figure 3) followed by the problem of interest. For each question, participants were asked to explain their reasoning, select their answer, and rate their confidence in their answer. Follow-up questions were then posed based on their responses, and students were asked whether their confidence or answer had changed after follow-up questioning. The interview was recorded on an iPad to capture student work and interview audio, which served as the data for the study along with interviewer notes.

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 3: The box question (ConcepTest #4497)

Follow-Up Questions

A semi-structured interview process was implemented in the think aloud protocol. The exact questions asked were dependent on the participant's reasoning pattern. Some common questions are listed in Table 1 with an associated indication by the participant's think aloud. The goal of the follow up questions is to fully understand, as much as possible, the student's line of thinking about the provided problem. This is the interviewer's chance to ask questions about what the student said or to direct the student to show more work to better understand the student.

Table 1: Follow-Up Question Examples

Student Indication	Follow-Up Question
The student stated the moment equation would change.	You mentioned the moment equation changes, can you talk more about that?
The student discussed the sign change for the moment but did not discuss with enough detail about how the direction of the resultant force changed.	You talked about the direction in terms of the sign, can you talk about how you determined the overall direction?
The student talked through the problem but did not draw anything.	Can you draw a free body diagram?
The student talked through the problem but did not write down any equations.	Can you write out your equations of equilibrium?
The student stated there is no change to the resultant because there is no reaction moment at the pin.	You mentioned there is no change to the resultant because there is no moment at the pin. Can you talk more about that?
The student evaluated the change in direction (CCW, CW) in a reaction moment.	The question asks about the resultant reaction force. Can you talk more about the reaction forces you are identifying?
The student didn't specify reaction forces in detail.	

Recruitment

Participants were recruited from a combined statics and deformable bodies course who elected to participate and were currently taking or had completed introductory physics. Students were from the same instructor across three sections at the United States Air Force Academy and 46 total interviews have been completed. As a part of our larger study, we performed a qualitative analysis on the question of interest for 13 of the 46 interviews (Figure 1). Interviews were conducted in accordance with an Institutional Review Board (IRB) approved protocol and attainment of informed consent.

Think Aloud Results

Thirteen students were given the rigid body beam concept question. Four answered correctly and nine students answered incorrectly (Table 2). Those who answered correctly showed a lower confidence level than those who answered incorrectly, also found in [2]. A higher confidence associated with incorrect answers is supported by the Dunning-Kruger Effect, originally proposed in [8] as a dual burden. The dual burden includes both poor performance and overestimation of performance. This effect indicates greater overestimation in lower performers relative to high performers and is shown in this small sample of students. Those who answered correctly did not elect to change their answer after follow-up questions but increased their confidence by 0.75.

Five students overall changed their confidence level after follow-up questions. Four of the five students indicate an increased confidence level and one student indicates decreased confidence. Table 2 shows confidence levels by answer correctness and the impact follow-on questions had on their confidence and whether students selected a different answer. After follow-up questions, the average confidence level increased for correct and incorrect answers. Correct answers increased from 2.75 to 3.5. Incorrect answers increased from 3.77 to 3.88.

Table 2: Answer Correctness, Confidence, and Answer Change

Initial Answer	Students	Average Initial Confidence	# Changed Answer	Average Final Confidence	Δ
Correct	4	2.75	0	3.5	0.75
Incorrect	9	3.77	5	3.88	0.11
All Students	13	3.46	5	3.76	0.3

After follow-up questions, five elect to change their answer. All students who elect to change their answer initially had the question incorrect and select another incorrect answer. Three students who change their answer indicate a change in confidence level with two increasing by one point and one student decreasing by one point. Those who elect to change their answer, in this small case study, indicate a higher average initial confidence level (3.80) than those who do not elect to change their answer (3.25) as indicated in Table 3.

Table 3: Confidence Level by Answer Change Status

	Initial Average Confidence	Final Average Confidence	Δ
Change Answer	3.8	4	0.2
Same Answer	2.88	3.62	0.74

Correct Answer Students (4)

Two of the four students who answered correctly had increased their confidence in their answer after follow-up questions. When reviewing student work, three students wrote equations of equilibrium and summed moments about A or B to solve the question. Only one student did not draw a free body diagram or write out equations. When reviewing the interview transcripts, all students quickly identified increased magnitude but not all had justification for the direction. One student who answered correctly stated:

> *"So if c gets bigger then* A_y *got to get bigger, which means that we're getting more in that upward force with that. ... So if that line gets bigger than this angle will increase."*

This student was able to identify the impact of dimension *c* on A_y and that an increase in A_y would increase the angle. This student drew a free body diagram and equations.

Incorrect Answer Students (9)

Eight students who answered incorrectly consider reactions. These students are concerned with the reaction force and moment changes and use "resultant reaction force" in their transcript. These students identify a change in reactions resulting from a dimension change and do not recall the concept of resultant force when prompted. Instead, students address the concept question regarding the reaction force or moment impact from the change in dimension. The remaining student who answers incorrectly assesses the dimension *c* does not impact magnitude and guesses a change in direction and selects that the direction increases.

When breaking down the eight students who assess their answer based upon reactions, two subgroups are identified: Group A and Group B. Group A assesses the question based upon the presence or no presence of a reaction moment at A. Group B assesses the question based upon the impact dimension *c* has on reaction forces at A.

One student who is a part of Group A stated:

> *"So if we were just looking at like A_x and A_y and nothing would change there. But if there was a moment involved, then that would change. But there's not because it's a pin."*

This student focuses on the presence or absence of a reaction moment at A to assess their answer. The student correctly identifies the reaction forces at A but thinks because there is no reaction force at A the result reaction force is unchanged. This student selects magnitude unchanged, angle decreases. It is clear this student did not have a reason to select the change in direction. It is worth noting that no answer choice allowed the student to selected magnitude unchanged and direction unchanged.

One student who is a part of Group B stated:

> *"So then pretty much, if c increases, that's not gonna change the reaction forces in the A_x direction. It will change the moment overall, but it will not change the reaction force."*

This student focuses on the impact of dimension *c* on reaction forces at A. While the student is correct that A_x will not change, the student does not identify By will increase in magnitude. This student selects the resultant reaction force will remain unchanged and the angle will decrease as their initial answer. It is clear this student did not have a reason to select the change in direction. It is worth noting that no answer choice allowed the student to selected magnitude unchanged and direction unchanged.

Five students are in Group A (Table 4). Three students identify a reaction moment at A and select the same initial answer: increase in magnitude and no change to direction. The remaining two identify no reaction moment at A and state that if there was a moment, the magnitude would change and select an answer choice that includes no change in magnitude. One student in Group

A sums the moment about A and draws a free body diagram. One student draws a free body diagram. Three students do not provide any work without prompting.

Table 4: Group A and Group B

Group	Description	#	FBD	Σ M	No FBD or Σ M
Group A	Reaction Moment	5	2	1	3
Group B	Reaction Forces	3	1	0	2

Three students are in Group B (Table 4) and select either: magnitude unchanged, direction decreases; magnitude unchanged, direction increases; or magnitude increases, direction unchanged. One student correctly identifies A_x does not change but A_y will increase and draws a free body diagram. The two other students talk generally about an increased lever arm from the change in dimension C. None of the students sum moments about any point without prompting. Reviewing follow-up questioning reveals all students do not think the direction changes because they are thinking about clockwise or counterclockwise moment applications from F_1. One student directly states that the direction will not change unless F_1 is applied in the opposite direction:

> *"So the resultant should act in the opposite direction of F_1, since that's the only force that's being applied to this. So as long as F doesn't change direction then the resultant force at A also shouldn't change direction."*

All Students (13)

Initially, seven students drew a free body diagram and four students summed moments about A or B. All students who choose on their own to sum moments about a point also drew free body diagrams. After prompting, only one student (Table 5, Student H) drew a free body diagram who had previously not drawn a free body diagram. After prompting, three students summed moments about A or B (Table 5, Students G, H, M) who did not do so initially. Students who did not implement a free body diagram or sum moments about A or B at any point are marked as "Other" in Table 5 (Student D & K). "Initial" in Table 5 indicates strategies implemented on their own while "Final" indicates strategies implemented after prompting.

Table 5: Breakdown of Problem-Solving Strategies for All Students (A-M)

		Other	Initial FBD	Initial Σ M	Final FBD	Final Σ M
Correct (4)			A	A		
Correct (4)			B	B	B	B
Correct (4)			C	C		
Correct (4)		D				
Incorrect (9)	Group A (5)		E	E	E	E
Incorrect (9)	Group A (5)	F				
Incorrect (9)	Group A (5)		G		G	G
Incorrect (9)	Group A (5)				H	H
Incorrect (9)	Group A (5)	I				
Incorrect (9)	Group B (3)		J			
Incorrect (9)	Group B (3)	K				
Incorrect (9)	Group B (3)		L		L	
Incorrect (9)						M

NOTE 1: Students were given new codes for ease of reading in alphabetical order down the table

NOTE 2: Students who choose to sum moments about B have their code in red. Those in black font choose to sum moments about A.

Conclusions

In this case study of 13 students, a correct answer is not correlated with a higher level of confidence. Instead, students indicate higher confidence, on average, when selecting incorrect answers, also seen in [2]. The students who elect to change their answer change their incorrect answer to another incorrect answer choice despite reporting a higher level of confidence. After follow-up questioning, the average reported confidence increased (0.3) for all students, regardless of answer correctness. However, incorrect answers saw a smaller increase in confidence (0.11) compared to correct answers (0.75).

Considering the eight of the nine students who answered incorrectly showed some level of consideration for reactions, it might be worth considering rewording the question, depending on what concept the instructor is desiring to evaluate. If instructors want to evaluate student understanding of resultant forces, then the current wording is adequate. If instructors want to evaluate student understanding of how a dimension change might impact reactions, asking for the impact to A_y, B_y, or A_x might be more suitable.

Future Work

Our qualitative analysis of thirteen student think alouds provides initial insights into the rigid body beam question shown in Figure 1 (ConcepTest #4660). The 13 participants in this work are a part of a larger sample of 46 interviews which investigate the box question shown in Figure 3 (ConcepTest #4497). Future work will explore the 46 interview sample for common themes and investigate the impact of follow-up questions on student confidence.

Disclaimer

The views expressed in this paper are those of the author and do not necessarily reflect the official policy or position of the Air Force, the Department of Defense, or the U.S. Government.

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