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Free-Body Diagram Performance with Problem Depictions at Different Levels of Abstraction

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Student Free-Body Diagram Performance with Problem Depictions at Different Levels of Abstraction

Abstract

Students typically practice drawing free body diagrams (FBDs) for abstract, textbook-style problems where extraneous details in the problem description and accompanying figures have been removed. Since practicing engineers often need to draw FBDs in more realistic contexts, an important question is: can students draw FBDs as well when faced with more realistic—less abstract—problem representations? To explore this question, students were asked to draw FBDs for problems with figures at different levels of abstraction: high abstraction (geometric shapes only), medium abstraction (line drawings of objects - like most textbook problems), and low abstraction (photographs of objects). Surveyed students were those in a first-year course, who had just learned to draw FBDs, and those in a third-year course, who were experienced with FBDs. The main finding was that student performance decreased with decreased abstraction (i.e., greater realism), but this was only the case for first-year students. This finding suggests that care should be taken in choosing the level of abstraction for problem representations used for FBD instruction. Students just learning to draw FBDs may be helped by highly abstract problem representations so that these problems are easier. But having experienced students wrestle with drawing FBDs in less abstract scenarios may help prepare them to draw FBDs in engineering practice. The results also suggest that instruction focused on helping students isolate bodies in more realistic or hands-on environments may be warranted for all students of mechanics.

Introduction

The ability to draw free body diagrams (FBDs) is arguably the principal skill students learn during an undergraduate mechanics education. A large body of literature exists concerning approaches to improve FBD instruction and practice [1,2]. Nevertheless, experienced students—and even practicing engineers—can struggle to know when and how to draw an FBD.

Students learning to draw free-body diagrams (FBDs) typically do so in abstract contexts: textbook-style problems in which extraneous details in the problem description and in accompanying figures have been removed. In contrast, practicing engineers must draw FBDs in realistic contexts, which raises an important question: can students draw FBDs in more realistic—less abstract—contexts? Anecdotally, several instructors have suggested that student performance decreases with decreased levels of abstraction in problem depiction, but this idea has not been empirically tested in the context of FBDs.

The issue of problem representation is well known in the physics literature. Several researchers in that field have investigated how different types of problem representations can aid or challenge student learning [3-5]. For instance, Kohl and Finklestein [5] showed that different problem representations (e.g. pictorial vs graphical vs verbal) impact student problem-solving competence and that the dependency is complex. Other researchers have attempted to use problems with additional context to expand the repertoire of student problem-solving strategies [6] or to harness student responses to different representations as a teaching tool [7]. Adding context to problems so they are more ambiguous and/or realistic is seen as advantageous in teaching students to solve real-world problems [8].

Recently, this investigator has also begun to look at the role of context in student problem solving in engineering. This research found that students perceive problems that have more context (i.e. more realism) as more challenging [9] and that students perform worse on such problems [10]. In these studies, context was added in the form of richer problem descriptions and additional images, but the primary problem image was identical in all cases. The effect of varying the primary problem image to reflect different levels of abstraction on student performance is unknown.

This study explores the question of whether the ability of students to draw FBDs is affected by the level of abstraction of the primary image shown in the problem description. Two student populations were surveyed: first-year students who had just learned to draw rigid body FBDs, and third-year students in their first dynamics course. Students were asked to draw FBDs for problems with accompanying figures at different levels of abstraction, and the FBDs were analyzed for errors.

Methods

Three problems were selected for inclusion in this study; students were asked to draw an FBD for the box of a dump truck, a lawn mower on a slope, and an overhang above a doorway. For each problem, three images of the scenario were developed: a photograph of the system (low abstraction), a line drawing of the system (medium abstraction), and a line-drawn image of the system in which most details identifying it as a real-world object were removed (high abstraction). Figure 1 shows the images used at each level of abstraction for each of the three problems.

Students in a first-year course, who had just learned to draw FBDs (the assessment was just prior to their first exam on the topic), and students in a third-year course, who were experienced with FBDs, were asked to draw FBDs for these problems. Each student population was randomly divided into three groups: A, B, and C. Each group saw each of the problems at one level of abstraction. Table 1 shows the abstraction levels assigned to each group for each of the three problems. Surveys were conducted in class with no discussion allowed between students and these surveys were not part of a graded assignment. Both student populations were most familiar with problems at the medium level of abstraction.

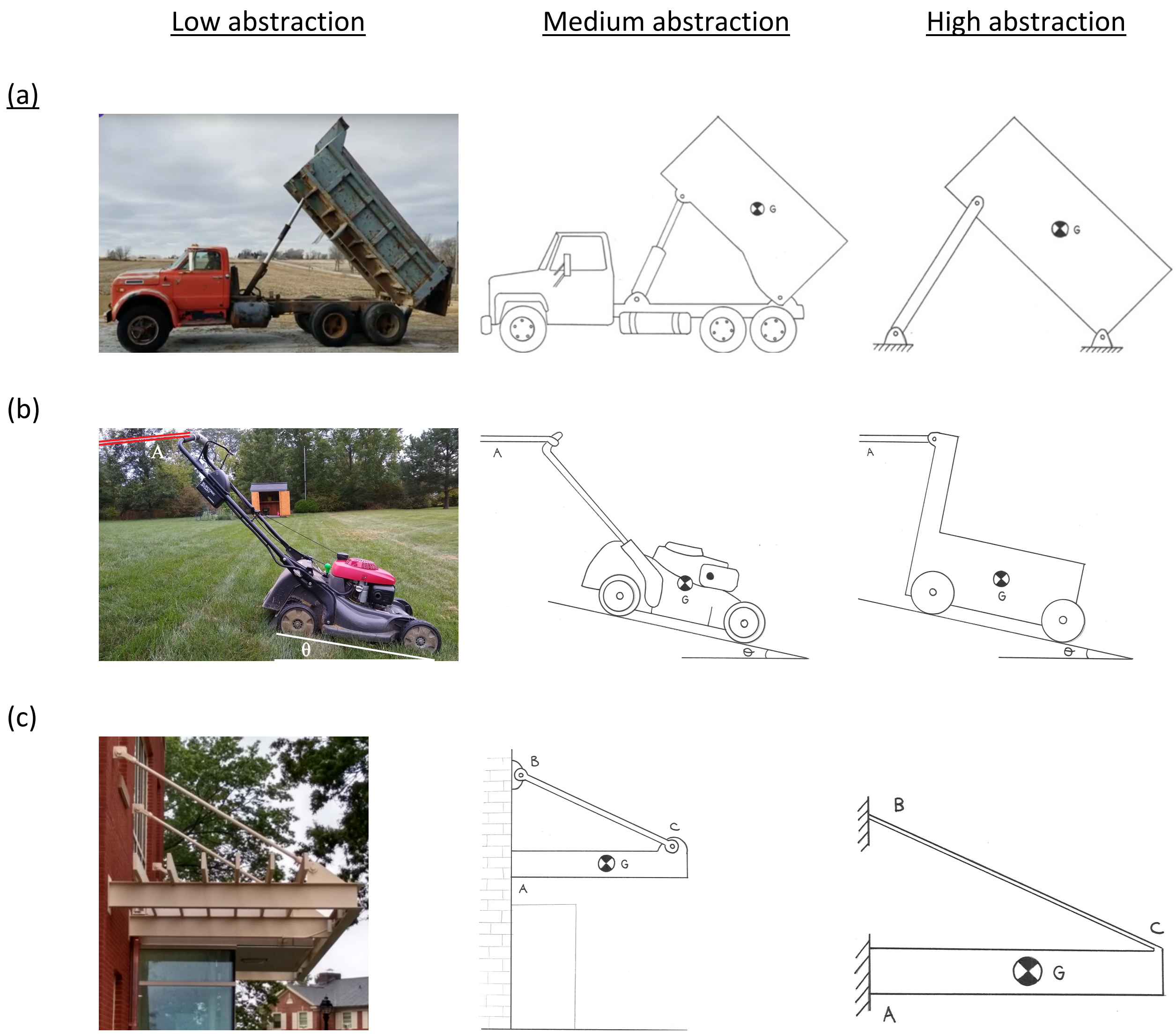


Figure 1: Images used for the (a) Dump Truck, (b) Lawn Mower, and (c) Overhang problems.

Table 1: Abstraction levels assigned to groups A, B, and C for each problem.

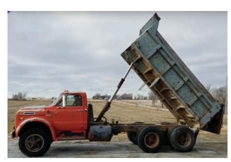
		Problem		
		Dump Truck	Lawn Mower	Overhang
Group	A	low	medium	high
	B	high	low	medium
	C	medium	high	low

For any given group, the high abstraction problem was presented first, followed by the medium abstraction problem, followed by the low abstraction problem. An example of the survey format is shown in Figure 2. After a brief description of the problem scenario, students were presented with the image associated with the abstraction level shown in Table 1 and asked to sketch an FBD. They were then asked to rate their confidence about the completeness and correctness of their FBD on a 5-point Likert scale ranging from very unsure (1) to very confident (5). They were also asked to provide, in as much detail as possible, a written description of any difficulties they had while drawing their FBD.

In the first-year class, 16 A, 16 B, and 14 C surveys were completed by students. In the third-year class, 23 A, 21 B, and 22 C surveys were completed by students. The completed surveys were analyzed by grading the student-drawn FBDs for correctness, and any errors were categorized according to type. The Likert-scale items and the student comments were also recorded. The error data were then used to calculate "errors per FBD" by dividing the total number of errors (or the number of errors belonging to a particular category) by the number of surveys in the group. This "errors per FBD" measurement allows average error rates to be compared across groups of different sizes. Note that the number of errors typically varied; many students had no errors while some students made several errors of different types. Mann-Whitney tests (adjusted for ties) were used to detect statistically significant differences between groups, with significance set a priori at $P < 0.05$.

FBD Survey B

A hydraulic cylinder is used to tip the box of a dump truck as shown in the figure. Pins connect the box of the truck to its other components. The combined weight of the box and the load has magnitude W and acts through the center of gravity (located somewhere in the dump truck box).



Q9: Draw a free body diagram of the box of the dump truck. **Do NOT solve the problem, only draw the diagram.**

Q10: How confident are you about the completeness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q11: How confident are you about the correctness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q12: Please describe any difficulties you had drawing the FBD in as much detail as possible.

3

Figure 2: An example survey page. Each survey consisted of three pages. All survey instruments are reproduced in the Appendix.

Results

The total number of errors made by each group of first-year students is shown in Figure 3(a). For the Dump Truck problem, there were significantly more errors at the medium abstraction level than at the high abstraction level ($P = 0.016$). There was also a trend toward more errors at the low abstraction level than at the high abstraction level, although the difference was not significant ($P = 0.234$). For the Overhang problem, there were significantly more errors at the low abstraction level than at the high abstraction level ($P = 0.046$). There was also a trend toward more errors at the medium abstraction level than at the high abstraction level, although the difference was not significant ($P = 0.162$).

The total number of errors made by each group of third-year students is shown in Figure 3(b). For the Overhang problem only, there were significantly more errors at the low abstraction level than at the high abstraction level ($P = 0.021$). There was also a trend toward more errors at the medium abstraction level than at the high abstraction level, although the difference was not significant ($P = 0.115$).

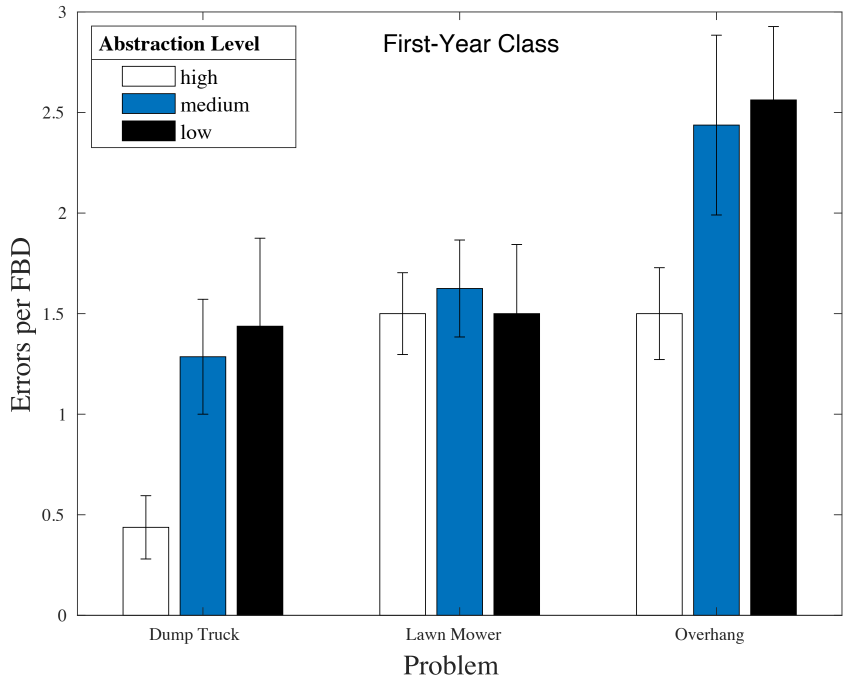
Despite some of these differences not being statistically significant (larger group sizes may have been necessary) these results suggest an inverse relationship between the number of errors and the level of abstraction, at least for the Dump Truck and Overhang problems.

Because of the trend shown in the Dump truck and Overhang problems, the results for these two problems were broken down further by error type. The errors per FBD classified according to error type are shown for both the first-year class and the third-year class in Figure 4 (Dump Truck problem) and Figure 5 (Overhang problem). The specific error types are indicated along the independent axis below the bars. It is clear some categories of error are associated with increased errors per FBD with decreased abstraction while others are not.

Discussion

Third-year students did significantly better on the FBD exercises than first-year students. This result is unsurprising, as students should continue to develop and refine their skills during an undergraduate program. At the time of the survey, first-year students were enrolled in statics, and third-year students were enrolled in dynamics. Between these two courses, students do not encounter significant formal instruction in drawing FBDs. Thus, the learning gains must be due to FBD practice. A natural question then arises: are there ways to improve the quality of FBD practice to further drive performance gains?

(a)



(b)

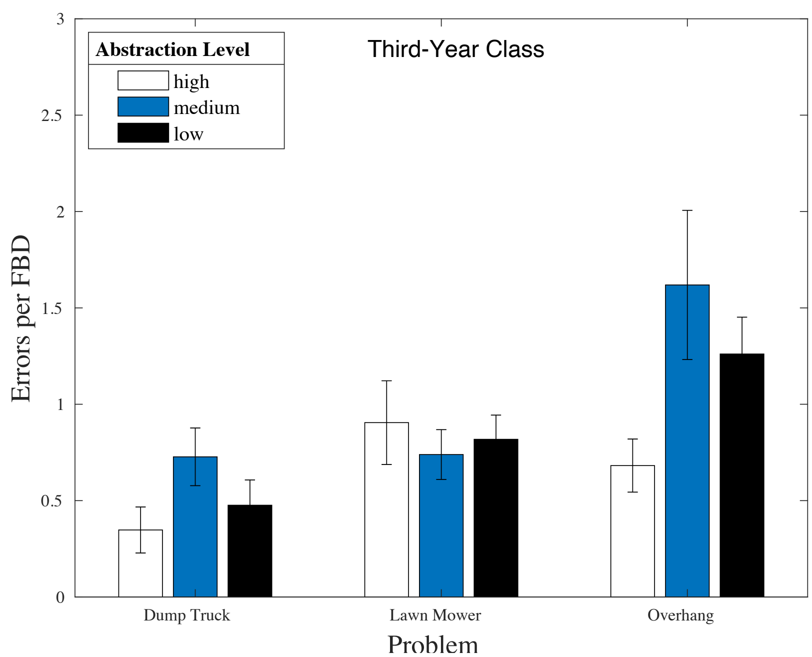
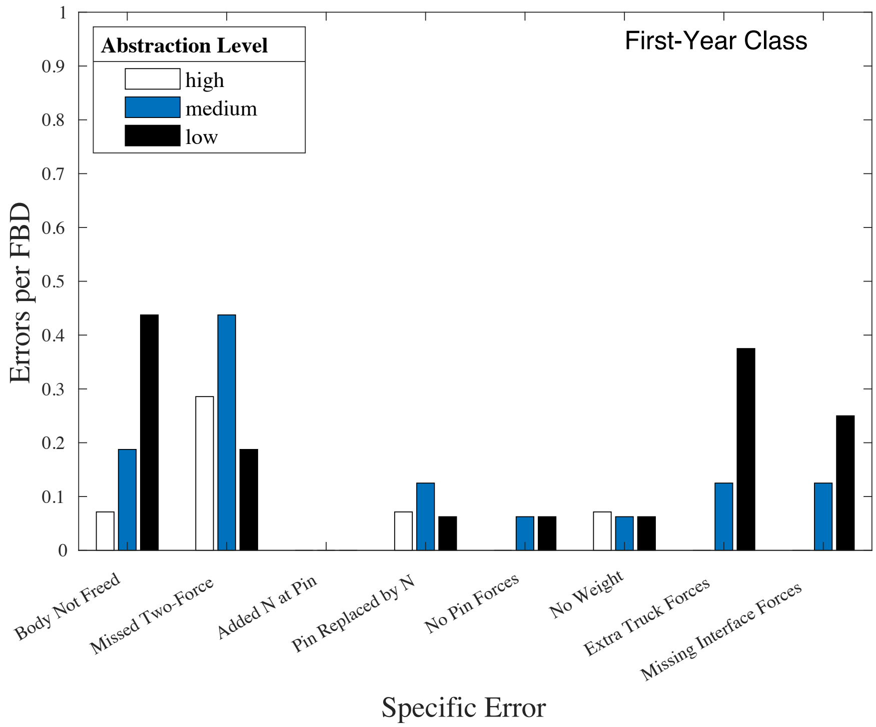


Figure 3: Total errors per FBD for three problems at different levels of abstraction for (a) a first-year class and (b) a third-year class. Bars represent the average number of errors per FBD for each group, and the accompanying error bars show the associated standard error.

(a)



(b)

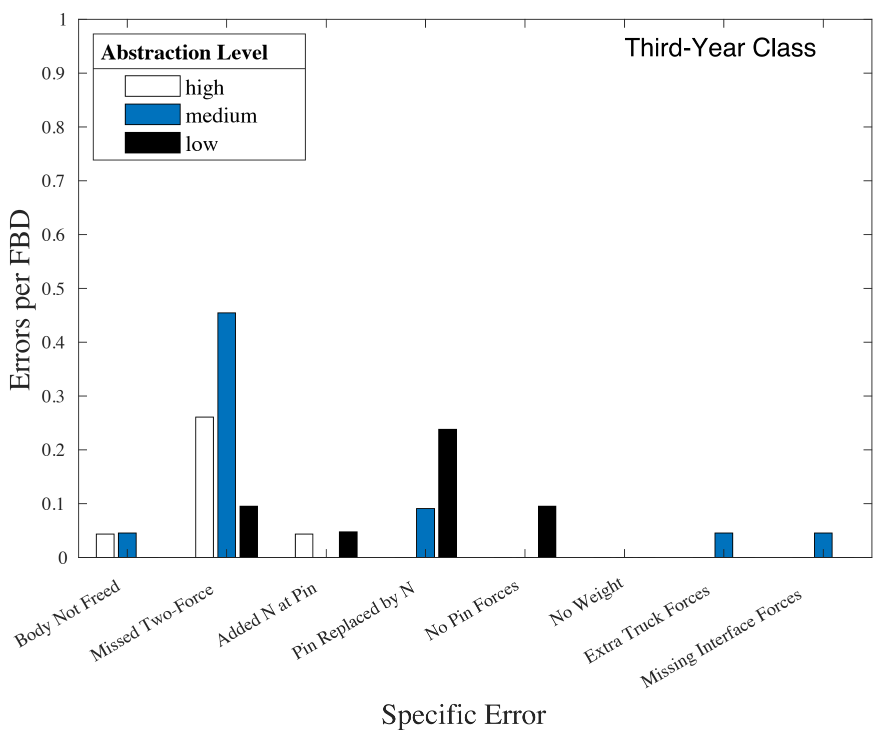
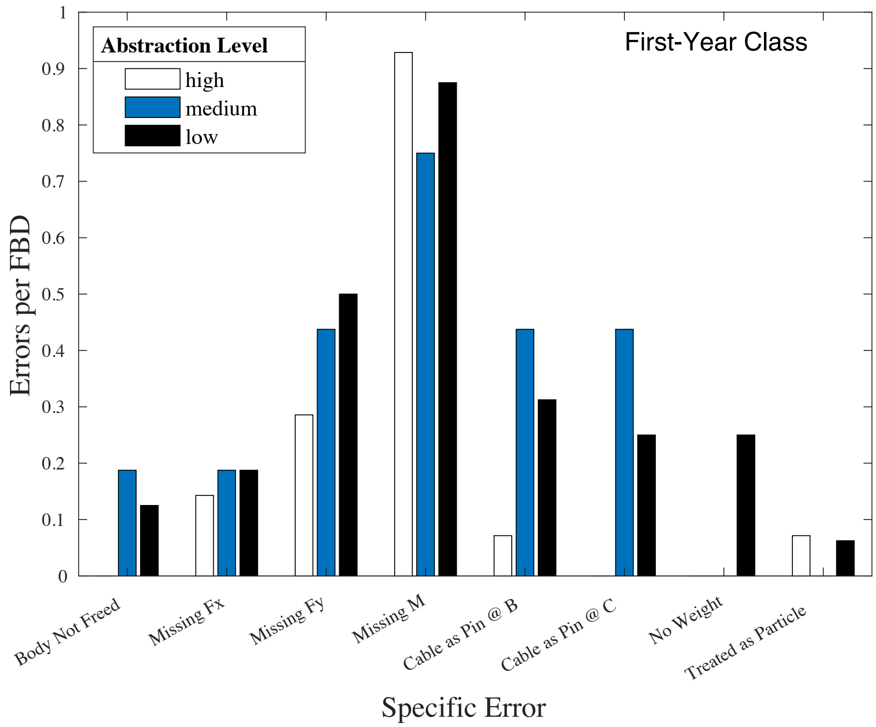


Figure 4: Errors per FBD for the Dump Truck problem categorized by error type at different levels of abstraction for (a) a first-year class and (b) a third-year class. Bars represent the average number of errors per FBD.

(a)



(b)

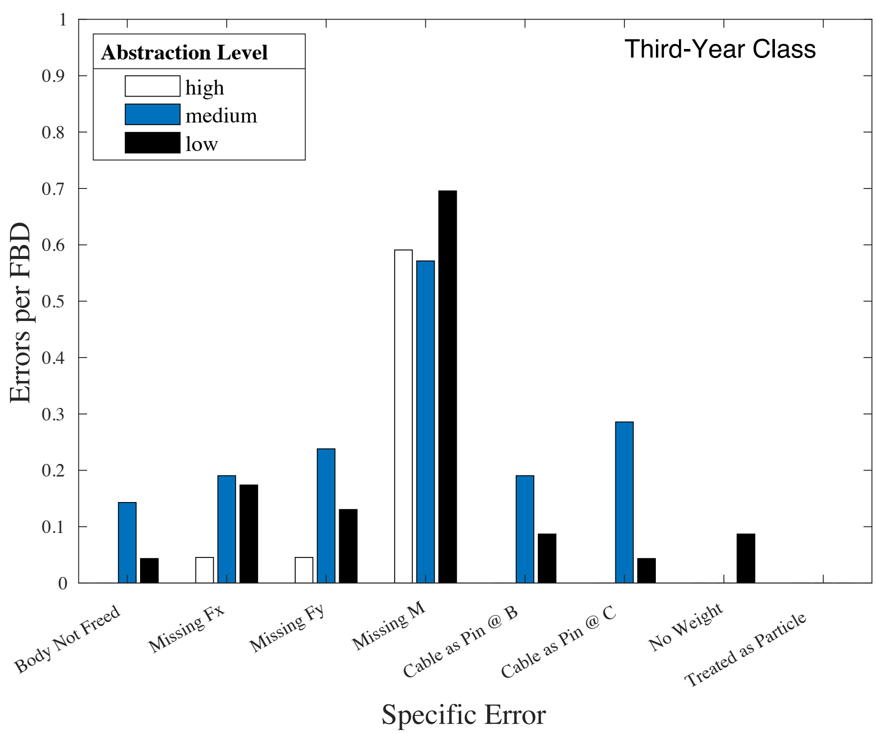


Figure 5: Errors per FBD for the Overhang problem categorized by error type at different levels of abstraction for (a) a first-year class and (b) a third-year class. Bars represent the average number of errors per FBD.

For two of the problems (Dump Truck and Overhang), the performance of the first-year students was reduced when these problems were presented at lower levels of abstraction (i.e. greater realism). For both problems, students made more errors with representations at the medium (line drawings of objects) or low (photographs of objects) levels of abstraction than at the high level of abstraction, as shown in Figure 3. A similar, albeit weaker, trend also appeared for the third-year students facing the Overhang problem. This finding suggests that the abstraction level should be chosen carefully depending on instructional objectives. Students just learning to draw FBDs may be helped by highly abstract problem representations so that these problems are easier. Having more experienced students wrestle with less abstract and even ambiguous scenarios when drawing FBDs may help prepare them to draw FBDs in the real world. Instructors may need to take an active approach to scaffolding FBD instruction with the intent of transitioning from high- to low-abstraction problem representations.

One potential explanation for why students perform better using highly abstract representations is that there is less cognitive load associated with these problems [11,12]. However, for both classes, the Lawn Mower problem featured similar numbers of errors across all levels of abstraction, which suggests that other explanations may be necessary. Because of the small size of this study, it is unclear what competing explanations are viable.

Exploring the specific errors that led to increased errors per FBD at lower abstraction levels is revealing. Figure 4(a) shows that for the Dump Truck problem, greater errors at the medium and low abstraction level for the first-year class were largely driven by issues with isolating the body. Some students didn't free the box of the truck (leftmost set of bars), and therefore also had extra forces associated with the truck on their FBD (second rightmost set of bars) and/or had missing forces between the truck and the box (rightmost set of bars). The third-year class was largely successful in separating the box of the truck as shown in Figure 4(b), and so error was relatively constant across all levels of abstraction.

Figure 5(a) shows that for the Overhang problem, greater errors at the medium and low abstraction level for the first-year class were again driven by issues isolating the body (leftmost set of bars) or with how to represent the force in the cable (fifth and sixth set of bars from left) - a critical connection to the larger environment. These same issues appeared for the more experienced students, as shown in Figure 5(b), but some issues with applying the fixed boundary condition at the wall also contributed to the trend of higher error with lower abstraction for these students. For both classes, the largest single error was missing the moment loading associated with the fixed boundary condition at the wall, but this error seemed to occur at the same rate regardless of abstraction level.

Student responses regarding confidence in the completeness and correctness of their FBDs did not seem to correlate with performance. Students expressing a great deal of confidence often made the same number of errors or more errors than students expressing little confidence. However, in responding to the prompt asking for a description of any difficulties they had drawing the FBD, some students could identify how they made an error (e.g. they expressed being unable to recall the type of support reactions for a fixed boundary condition).

Conclusion

This paper provides evidence that the level of abstraction of the primary image of a problem description can impact student performance in drawing an FBD. For two of the three problems investigated in this paper, lower abstraction (i.e. greater realism) led to lower performance for a first-year engineering class, who had recently learned to draw rigid body FBDs. Most of the additional error accrued with less abstract representations was due to student difficulty in isolating the body and/or dealing with boundary conditions. A more experienced, third-year class facing the same problems had less difficulty transitioning between different levels of abstraction, although the trend of reduced performance with decreasing abstraction was present for one of the problems for this group as well.

Overall, these results suggest that care should be taken in choosing the level of abstraction for problem representations used for FBD instruction, with more abstract representations potentially being helpful as early learning tools. These results also suggest that instruction focused on helping students to isolate bodies in more realistic or hands-on environments may be warranted for all students of mechanics. Future work investigating what enables students to draw FBDs in less abstract contexts is also worthwhile, as it may lead to teaching tools that help students draw FBDs in more realistic scenarios.

Acknowledgements

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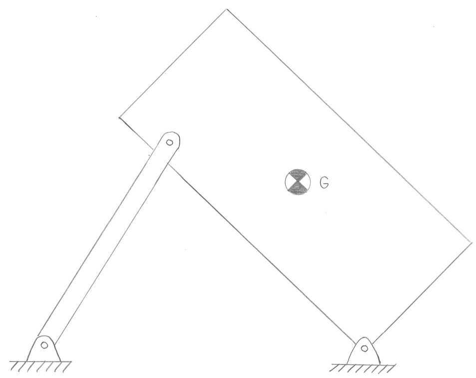
Appendix: All Survey Instruments

The rectangle is supported as shown in the figure. It has a weight W that acts through the center of gravity at G.



Q1: Draw a free body diagram of the rectangle. **Do NOT solve the problem, only draw the diagram.**

Q2: How confident are you about the completeness of your FBD?

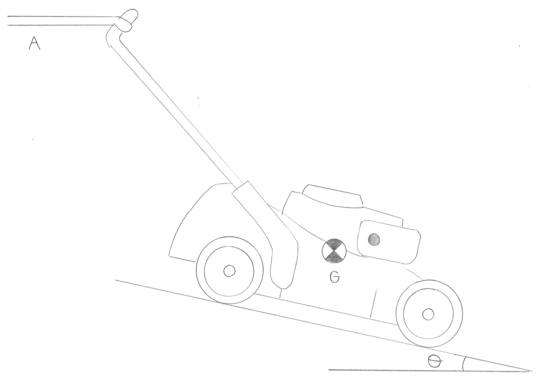
Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q3: How confident are you about the correctness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q4: Please describe any difficulties you had drawing the FBD in as much detail as possible.

The lawnmower is being pulled up the hill of slope θ due to tension in the cable at A. It has a weight W that acts through the center of gravity at G. Neglect any friction.



Q5: Draw a free body diagram of the lawnmower. **Do NOT solve the problem, only draw the diagram.**

Q6: How confident are you about the completeness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q7: How confident are you about the correctness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q8: Please describe any difficulties you had drawing the FBD in as much detail as possible.

The overhang of a building is supported as shown in the figure. It is fixed at A and attached to a tension member pinned at B and C. The overhang has a weight W that acts somewhere along its length.

Q9: Considering a 2D cross-section of the overhang (i.e. thinking about only closest beam running from A to C and ignoring interactions into the page), draw a free body diagram of the building overhang. **Do NOT solve the problem, only draw the diagram.**

Q10: How confident are you about the completeness of your FBD?

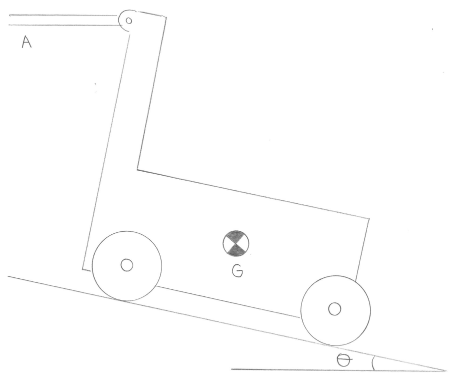
Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q11: How confident are you about the correctness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q12: Please describe any difficulties you had drawing the FBD in as much detail as possible.

The L-shaped body is being pulled up the hill of slope θ due to tension in the cable at A. It has a weight W that acts through the center of gravity at G. Neglect any friction.



Q1: Draw a free body diagram of the L-shaped body. **Do NOT solve the problem, only draw the diagram.**

Q2: How confident are you about the completeness of your FBD?

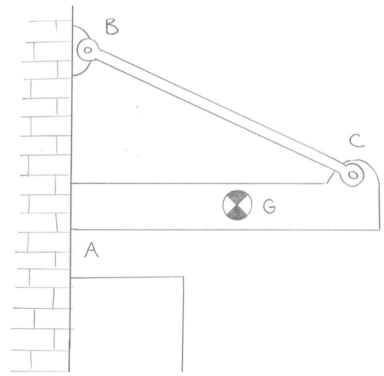
Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q3: How confident are you about the correctness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q4: Please describe any difficulties you had drawing the FBD in as much detail as possible.

The overhang of a building is supported as shown in the figure. It is fixed at A and attached to a tension member pinned at B and C. The overhang has a weight W that acts through the center of gravity at G.



Q5: Draw a free body diagram of the building overhang. **Do NOT solve the problem, only draw the diagram.**

Q6: How confident are you about the completeness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q7: How confident are you about the correctness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q8: Please describe any difficulties you had drawing the FBD in as much detail as possible.

A hydraulic cylinder is used to tip the box of a dump truck as shown in the figure. Pins connect the box of the truck to its other components. The combined weight of the box and the load has magnitude W and acts through the center of gravity (located somewhere in the dump truck box).

Q9: Draw a free body diagram of the box of the dump truck. **Do NOT solve the problem, only draw the diagram.**

Q10: How confident are you about the completeness of your FBD?

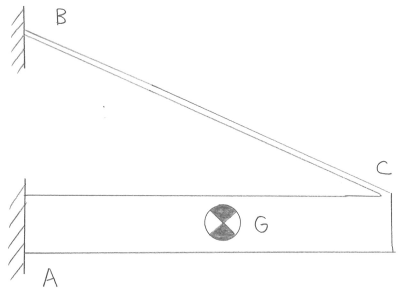
Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q11: How confident are you about the correctness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q12: Please describe any difficulties you had drawing the FBD in as much detail as possible.

The rectangle is supported as shown in the figure. It is fixed at A and connected to a support cable running from B to C. The rectangle has a weight W that acts through the center of gravity at G.



Q1: Draw a free body diagram of the rectangle. **Do NOT solve the problem, only draw the diagram.**

Q2: How confident are you about the completeness of your FBD?

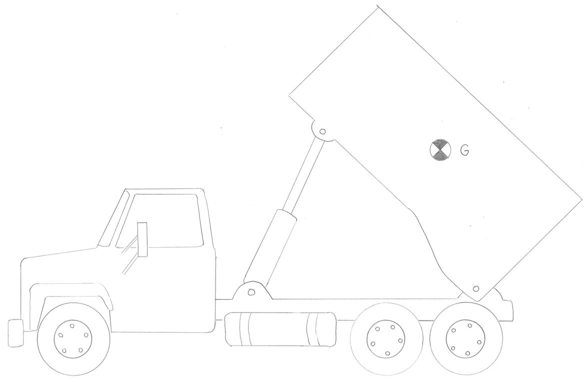
Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q3: How confident are you about the correctness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q4: Please describe any difficulties you had drawing the FBD in as much detail as possible.

The hydraulic cylinder is used to tip the box of the dump truck shown in the figure. Pins connect the box of the truck to its other components. The combined weight of the box and its load has magnitude W and acts through the center of gravity G.



Q5: Draw a free body diagram of the box of the dump truck. **Do NOT solve the problem, only draw the diagram.**

Q6: How confident are you about the completeness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q7: How confident are you about the correctness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q8: Please describe any difficulties you had drawing the FBD in as much detail as possible.

The lawnmower is being pulled up the hill of slope θ due to tension in the cable at A (highlighted red). It has a weight W that acts through the center of gravity (located somewhere between the wheels of the mower). Neglect any friction.

Q9: Draw a free body diagram of the lawnmower. **Do NOT solve the problem, only draw the diagram.**

Q10: How confident are you about the completeness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q11: How confident are you about the correctness of your FBD?

Very Unsure	Unsure	Neutral	Confident	Very Confident
☐	☐	☐	☐	☐

Q12: Please describe any difficulties you had drawing the FBD in as much detail as possible.