Inconsistencies in Students' Approaches to Solving Problems in Engineering Statics

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Abstract – **This paper looks at students' responses to two concept questions: one on equilibrium and one on equivalence, which is an equilibrium problem from a different perspective. Student responses were from final exam questions that included explanations and from national Statics Concept Inventory (SCI) data. Examination of students' explanations to these two questions shows that students are not consistent in their assessment of force and moment equilibrium, and a mapping of the explanations onto the answer distributions implies the same result is true for the national SCI data. The conclusion of this study is that most students are influenced by context when assessing equilibrium.**

Index Terms – Statics, Specific difficulties, Misconceptions.

INTRODUCTION

The term 'misconception' is commonly used in engineering education to describe an incorrect understanding that must be unseated and replaced with a correct understanding, but there is an alternative theory in Physics Education Research that student difficulties are influenced by context if not outright context dependent [1]-[6]. In this view students' incoming understanding is made up of bits of loosely connected knowledge referred to as phenomenological primitives (p-prims) [1]-[5] or facets of thinking [6]. These p-prims, or knowledge elements, are triggered by context; while they may individually be correct in some circumstances, they may be applied in the wrong circumstances or combined improperly to form incorrect conclusions. According to this view, students do not need to have misconceptions unseated; instead they must learn which elements are correct in which contexts. These elements provide building blocks for reaching the desired mode of thinking. In this terminology, instead of misconceptions, students exhibit "specific difficulties" [7] – some more commonly than others. In order to design effective instructional material and techniques, one should take students' specific difficulties into account [8],[9]. This work aims to demonstrate that engineering education should also begin to acknowledge the contextual influence of students' specific difficulties.

In Engineering Statics equilibrium and equivalence are fundamental concepts that require students to apply the same methods. In both cases students must consider linear and rotational acceleration (or lack thereof) in order to guarantee that conditions are satisfied; in essence an equivalence problem is an equilibrium problem from a different perspective. As such, the tools and methods for solving equilibrium and equivalence problems are the same. Previous studies have shown that students either conflate linear and rotational acceleration or consider only one of them in many cases [10]-[15]. As a result, if these are deep-seated misconceptions, it would follow that students would display consistent performance on equilibrium and equivalence problems.

Consistency v. Inconsistency

Since inconsistency is the key aspect of the argument here, it is necessary to be specific about how student consistency and inconsistency are defined. Quite simply, consistency is defined as using the same approach to the same type of problem in different situations, and inconsistency therefore is a lack of consistency. There are four ways in which a student could display consistent behavior: 1) always assess force and moment equilibrium; 2) always assess force, but never assess moment equilibrium; 3) never assess force, but always assess moment equilibrium; and 4) never assess force or moment equilibrium. Of the four it is obvious that the first is the desired behavior, but the other three also represent a consistent, if incorrect, approach. All other behaviors for assessing equilibrium on multiple problems are therefore labeled as inconsistent.

To test the consistency of student behavior, a total of 140 students in three Statics classes from different terms but taught by the same person at Western Washington University (WWU), were asked to solve and explain both an equilibrium and an equivalence concept question. Students' explanations were then reviewed and coded to determine whether or not they had addressed force and moment equilibrium consistently as defined above.

The Statics course at WWU, which has a pre-requisite of one quarter of physics (mechanics), is organized around five topics: free body diagrams, equilibrium, equivalence, separation of rigid bodies, and friction, without differentiation between two vs. three dimensional cases, concurrent vs. non-concurrent force systems, and single bodies vs. frames and trusses [16]. These situations are all addressed in the course, but not in the order of traditional textbooks. Otherwise the course is a standard lecture-based course with homework, midterms, projects, a final exam, a limited number of think-pair-share exercises, and weekly Warm Up exercises for the first eight weeks of the quarter [17].

In addition to the WWU responses, the distributions of 1342 students' answer selections on the same questions on the Statics Concept Inventory (SCI) were reviewed to see what they imply about student behavior on equilibrium questions. This paper builds off of previous studies of students' responses to Engineering Statics concept questions, explains the questions and methodology used in the study, and presents the results for both the students from WWU whose answers include explanations and the national SCI results.

THE QUESTIONS

This study compares student responses on two concept questions from the Statics Concept Inventory (SCI) [18] using two different data sources: 140 final exam responses that include explanations from students at WWU, and 1342 responses that do not include explanations from students at schools around the nation.

The final exam for the Statics class at WWU contains five questions from the SCI in addition to five traditional problems. For each SCI question students are required to explain why the answer they have selected is correct or why the other answers are incorrect. This structure allows the instructor some insight into students' thinking on these questions. This study focuses on two of those five questions: one on equilibrium and one on equivalence.

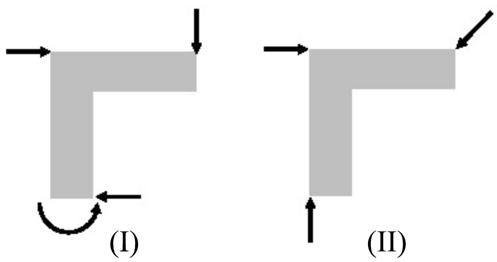

FIGURE 1
BODIES UNDER CONSIDERATION FOR THE EQUILIBRIUM QUESTION

The equilibrium question asks students to consider the two bodies shown in Figure 1, and to determine which of the following statements is correct:

(a) I could be in equilibrium; II could be in equilibrium.
(b) I could never be in equilibrium; II could never be in equilibrium.
(c) I could be in equilibrium; II could never be in equilibrium.
(d) I could never be in equilibrium; II could be in equilibrium.
(e) Cannot say without more information.

The correct answer is (b); it is not possible for either system to be in equilibrium. Body (I) has an unbalanced vertical force, which means force equilibrium is impossible; body (II) has balanced linear forces, but they are arranged in a manner that guarantees an unbalanced moment. This is the most difficult question on the SCI, and student responses to it have been extensively studied [11]-[13],[15]. Table I shows the answer distributions for the WWU and national SCI data for the equilibrium question. According to previous studies, students who select (a) are most likely to have considered moment equilibrium on the first body and force equilibrium on the second body, although there are other common errors that lead to students selecting (a). Students who select (b) correctly justify their answer selection in roughly 90% of cases, although some students only mention the conditions that are necessary to support their conclusion (force equilibrium on the first body and moment equilibrium on the second body). Students who select (c) almost all only consider moment equilibrium, and students who select (d) almost all only consider force equilibrium. For additional information on student thinking on this question see [11]-[13],[15].

TABLE I
EQUILIBRIUM QUESTION ANSWER DISTRIBUTIONS

Data Set	n	a	b	c	d	e
WWU	140	9%	45%	19%	26%	0%
National SCI	1342	28%	16%	26%	29%	1%

The equivalence question asks to students to find an equivalent system to the one shown on the left-hand side of Figure 2. The question states that the body is subject to forces on its lower portion, and it is kept in equilibrium by the 5N force that is shown. Students are then asked which of the other five systems shown would be able to maintain equilibrium if the other forces remain the same. The correct answer is (b). Only systems (b) and (e) maintain force equilibrium, and of those two only system (b) maintains moment equilibrium. However, answer (a)-(d) all appear to maintain moment equilibrium if one only considers the top point. Table II shows the answer distributions for the WWU and national SCI data for the equivalence question.

TABLE II
EQUIVALENCE QUESTION ANSWER DISTRIBUTIONS

Data Set	n	a	b	c	d	e
WWU	140	10%	73%	6%	2%	9%
National SCI	1342	30%	35%	11%	9%	15%

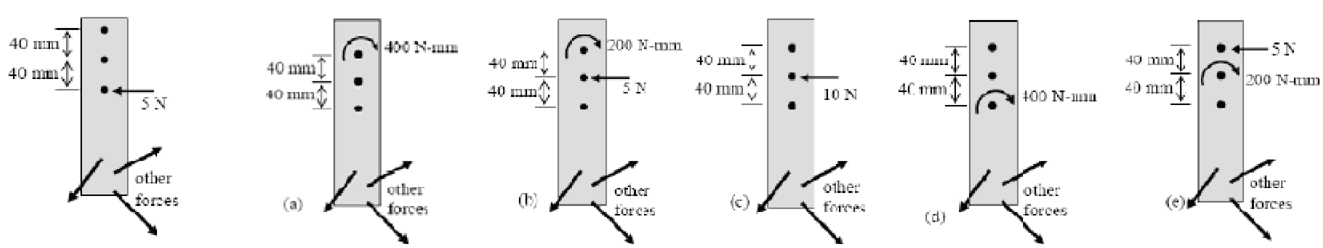

FIGURE 2
ORIGINAL SYSTEM AND ANSWERS FOR THE EQUIVALENCE QUESTION

Coding the WWU Responses

For the WWU data, student explanations of their answer choices for the two questions were coded for whether or not the student considered force and moment equilibrium. For the equilibrium question the coding scheme used is a modified version of the coding scheme used in [15]. The original coding scheme rated the students by both whether they cited force and moment equilibrium and whether they cited it where it was necessary to reach the correct conclusion. Thus students were rated separately for force and moment equilibrium on a four point a scale as follows: 1) Never cited; 2) Cited, but not where needed; 3) Cited only where needed; and 4) Always cited. 67 of the 140 responses had already been coded using this scheme for the projects described in [11]-[13],[15], so the remaining 73 responses were coded using the same scheme. However, because there is only one body to consider in the equivalence question, the coded data for the equilibrium question was simplified for comparison purposes. Students who received a rating of 3 or 4 on either force or moment equilibrium were recoded as having considered that type of equilibrium, while students who received a 1 or 2 were recoded as having not consider that type of equilibrium. While the recodings of 1 and 4 are obvious, those of 2 and 3 require brief explanation. It is proper to recode a 2 as not considering that type of equilibrium because the student failed to consider it in the case where it was required to reach the correct conclusion. It is also proper to recode a 3 as having considered that type of equilibrium because it was cited where it was needed, and the student is given the benefit of the doubt on the other body as having not cited that type of equilibrium because it was not necessary for a correct explanation. For the WWU final exam responses 71% of students considered force equilibrium and 64% of students considered moment equilibrium on the equilibrium question.

Due to the fact that there is only one body to consider for the equivalence question, the coding scheme used for it is much simpler. Students were coded for both force and moment equilibrium as: yes, they cited it, or no, they did not cite it. For the WWU final exam responses 68% of students considered force equilibrium and 97% of students considered moment equilibrium on the equivalence question. It is not possible to explain why the rate of consideration of moment equilibrium is so high on this question. If one enters into speculation there are three obvious possible explanations: 1) students associate equivalence with consideration of moment, 2) the couple symbol on most of the answer choices influences students' approach to the problem, and 3) the necessary inclusion of numbers in equivalence problems leads students to a different mode of thinking. These possible explanations raise interesting questions for future research on which the data for this project cannot be used to shed any further light, but all three are consistent with the basic premise that student behavior is inconsistent and affected by context. What the data can explicate is that the overwhelming majority of students (just over 92%) who selected answers (a), (c), or (d) on the equivalence question did not consider force equilibrium (the remainder either just mentioned it without actually assessing it or assessed it incorrectly). There were also students (just under 20%) who selected (b) or (e) who did not consider force equilibrium on this problem, and it should be noted that you can get the correct answer and provide a correct justification for it by considering only moment equilibrium. To do so one must calculate moment equilibrium on each possible answer at multiple points. Of course the interesting issue is not this particular question, but how student explanations of and performance on the two questions compare to each other. Table III summarizes the basic data for the WWU responses.

TABLE III
WWU RESPONSE SUMMARY

Question	n	% Correct	% Considered F	% Considered M
Equilibrium	140	45%	71%	64%
Equivalence	140	73%	68%	97%

COMPARISON OF THE QUESTIONS

Comparisons were made for both the WWU response data and the national SCI data, but due to the different types of data the two comparisons are slightly different. The comparisons of the WWU data were made using the codings of the student responses. The comparisons of the national SCI data were made using inferences of what types of equilibrium students considered based upon answer pairings.

The justification for this approach to analyzing the national SCI is strong on the equilibrium question, as it was shown in [13] that student explanations for this question were consistent for students at different universities even though the distribution of answers were not. Thus the conclusion is that students who answered (b) or (d) considered force equilibrium on both bodies, and students who answered (b) or (c) considered moment equilibrium on both bodies. The realistic error expectation of these conclusions is on the order of 10%, and it was shown in [13] that some students who selected (a) did consider both force and moment equilibrium (although not as conditions that had to be met at the same time) and almost 10% of students who selected (b) did not provide a correct explanation with their correct answer choice.

The justification is not as strong on the equivalence question, as there has not been an analysis of student explanations for this question for students at multiple universities. Therefore, the assumption used for the national SCI data is that the WWU explanations are representative of those that would be found at other schools (which was shown to be true for the equilibrium question). The result of this assumption is that one must conclude that almost all students considered moment equilibrium for this question, but that those who selected (a), (c), or (d) as an answer were only 8% likely to have considered force equilibrium too. Thus another obvious area for future research is to get additional samples of student explanations of their answer selection on this or some other equivalence question.

WWU Data

The coded responses from WWU show the inconsistency of students' assessment of equilibrium. Table IV gives the summary information for the coding of student responses when compared across the two questions. When the two types of equilibrium are looked at separately, as they are shown in the first two lines of Table IV, it is clear that at least one-third of students assessed force or moment equilibrium on only one of the two questions. The remaining roughly two-thirds of responses appear to be consistent, but the story is not quite that simple. In fact, as is shown in the third line of Table IV, just over 40% of the students were consistent in that they either always assessed force and moment equilibrium or always assessed only force or moment equilibrium and ignored the other. The remaining almost 60% of the students were inconsistent in their approach to the two questions in that they assessed each one at least once, but did not assess either twice.

TABLE IV
CONSIDERATION OF EQUILIBRIUM FOR WWU DATA

Equilibrium Considered	n	On Both Questions	On Only One Question	On Neither Question
Force	140	53%	33%	14%
Moment	140	61%	39%	0%
Force & Moment	140	32%	45%	23%†

†Of these 12 students (9% of the total number) were consistent in their approach to the two questions.

To be able to extend an analysis of student consistency to the national SCI data it is necessary to see how the codings correspond with answer selections for the WWU data. Assuming that the thinking for the equivalence question is similar for students at different schools, as it was shown to be for the equilibrium question, it is possible to estimate the fraction of students that were likely to have been consistent for the national SCI data. Table V compares the answer selections for the WWU students with their consistency. The entries in the table are the number of students who were consistent and the total number of students for each answer combination for the two questions. Of the 56 students who demonstrated consistency on the two questions, 44 of them assessed force and moment equilibrium on both questions. The remaining 12 students who were consistent, but incorrect, in their approach all focused on moment equilibrium exclusively. Of these students, 2 had the answer combination (b)/(b), 5 had (c)/(a), and 5 had (c)/(b).

TABLE V
WWU STUDENT CONSISTENCY BASED ON ANSWER SELECTIONS

Equilibrium Answer		a	b	c	d	e
Equivalence Answer	a	0/4	0/2	5/5	0/3	0/0
	b	0/6	38/47	6/19	3/30	0/0
	c	0/0	0/3	0/2	0/4	0/0
	d	0/1	0/2	0/0	0/0	0/0
	e	0/2	4/9	0/1	0/0	0/0

Table V shows that there are a limited set of answer combinations where students displayed consistency in their assessment of force and moment equilibrium. Students fell into four groups: 1) students (36) who selected (b)/(b) and provided sufficient explanations to both questions; 2) students (4) who selected (b)/(e) and provided a sufficient explanation to the equilibrium question, but failed to correctly calculate the moment on the equivalence question; 3) students (4) who selected (c)/(b) or (d)/(b) who provided correct and sufficient explanations for both questions, but inexplicably selected the incorrect answer to the equilibrium question; and 4) students (12) who selected (b)/(b), (c)/(a), or (c),(b) who always assessed moment equilibrium, but never assessed force equilibrium.

These results are not surprising. Based solely upon the answer choices one would expect the (b)/(b) and (b)/(e) answer combinations for students who do consider both force and moment equilibrium and (c)/(any) for students who only consider moment equilibrium. Moreover, it is consistent with past studies of the equilibrium problem that roughly 10% of answer selections will not be supported by their accompanying explanation, with slightly more correct answers having incorrect explanations than the opposite case [13],[15]. None of the answer combinations other than the four mentioned above imply that a student has considered equilibrium consistently, and few apparently do. Only 40% WWU students displayed consistency, and they congregated in a limited number of answer combinations.

Students who displayed consistency on the conceptual questions also performed better when writing force and moment equilibrium equations on traditional problems. For the five traditional problems on the final exam students who displayed consistency on the equilibrium and equivalence question scored 7% higher on that portion of the final exam, and students who were both consistent and correctly answered both the equilibrium and equivalence questions scored 8% higher on that portion of the final exam. The differences are both statistically significant ($p < 0.001$), and they are consistent with the findings in [19] that students who make errors on the SCI are also likely to make the same types of errors on traditional problems.

National SCI Data

The information gleaned from the patterns in the explanations in the WWU lead to some interesting conclusions about the National SCI data. While it is not possible to make strong statements about the exact number of students who did or did not display consistency, it is possible to do some bounding and show that consistency is not the norm. Table VI shows the answer distributions for the national SCI data. While the distribution of answers is different than the WWU data, it is reasonable to believe that the patterns of thinking were similar [13].

TABLE VI
NATIONAL SCI ANSWER DISTRIBUTION

Equilibrium Answer		a	b	c	d	e
Equivalence Answer	a	11.2%	3.4%	8.8%	6.4%	0.4%
	b	6.1%	7.6%	8.5%	13.0%	0.3%
	c	4.0%	1.6%	2.7%	2.6%	0.1%
	d	3.0%	1.3%	1.9%	2.1%	0.4%
	e	3.6%	2.1%	4.0%	4.8%	0.1%

As a thought experiment, consider several possibilities of the maximum fraction of students who may have displayed consistency according to the national SCI data. One possibility is to use the strict logic that only answer combinations (b)/(b), (b)/(e), (c)/(any) could be reached with a consistent approach to equilibrium assessment. According to the answer distribution, 35.6% of responses are in these answer categories, and this assumes that all of these students displayed consistency, which is not consistent with the WWU coding results. Another possibility is to map the WWU coding responses onto the national SCI data and assume that answer combinations (b)/(b), (b)/(e), (c)/(a), (c)/(b), and (d)/(b) imply consistency. According to the distribution 40.0% of responses are in these answer categories, and this once again assumes that all of these students displayed consistency. There are many ways that one could try to prorate the responses in the national SCI data based upon the WWU response coding, all of which would have great uncertainty due to some of the small numbers of responses in the WWU data, but all of which would result in a reduction of the fraction of students in the national SCI data who displayed consistency. So even by the most generous assessment that 80% of students in those categories displayed consistency (since that was roughly the case for (b)/(b) respondents for the WWU data) one finds that at most a third of the students in the national SCI data displayed a consistent approach to equilibrium for these two problems, and the actually number is probably much lower. The actual fraction of students, however, is not as important as the implication that the majority of students faced with multiple problems that require them to assess equilibrium do not apply a consistent approach to solving these problems.

IMPLICATIONS

The problems we are faced with when trying to teach students how to assess equilibrium are two-fold: 1) Even at the end of the class too many students cannot solve problems that require them to assess equilibrium. Only one third of the WWU students answered both questions correctly, and fewer than 10% of students nationally answered both questions correctly. 2) The errors that students make, according to their own explanations and their answer selections, are inconsistent. Students' approaches to problems that require assessment of equilibrium vary from problem to problem.

The latter of these two issues implies that students do not have misconceptions that need to be unseated, but that they are reacting to something in the context of the problems. The challenge that this in turn creates is that as engineering educators we need to begin to learn what sorts of situations or clues lead students to take one approach at one time, and what other situations or clues lead them to take another approach at another time. We need to begin to develop an understanding of the building blocks that students are using to construct their approaches, and then learn how to help students build to the correct approaches in different situations. The two problems considered here offer several possibilities including the three mentioned earlier: 1) associations with the word equivalence, 2) associations with an applied couple, and 3) the inclusion of numbers in the one problem. It may be one, some, all, or none of these things, but it appears that the majority of students react to context before determining their approach to equilibrium problems. We need to begin to determine the building blocks that students are using to construct their approaches to these problems to help them learn to build correct approaches in multiple circumstances. It seems to this author that if we continue to approach students' specific difficulties as misconceptions we will end up trying to solve student problems with equilibrium one case at a time, but if we can take step back, we can hopefully develop some approaches that will help students achieve consistent results in a variety of situations.

Another way to approach the problem might be to find approaches or exercises that help students apply method more consistently in different contexts and let those activities that work help guide us to a better understanding of how students construct their approaches. Since introducing SCI questions for warm-up exercises and final exam questions, I have tried to address approaches to equilibrium through various means with limited success. Warm-up exercises are useful because they allow for examination through class discussion of why an incorrect answer seems plausible (i.e. what feature(s) of the problem misled you?). In addition I have introduced some think-pair-share exercises (especially in the equivalence lectures), some crude computer animations of what happens when parts are not in equilibrium, and computer problems where students must find forces that maintain equilibrium as something on the system extends through a range (e.g. a cylinder extends). I have found it helpful on the computer problems to have a poorly designed system, such as a cable that switches to a compressive load or a load that exceed the input capacity at some point, to get students to think about the limitations (and potential disasters) of real systems. While I anecdotally believe that these various approaches help student understanding, there have only been small gains on the equilibrium question (from 2 in 6 correct to 3 in 6 correct) and no significant change in the equivalence question during the time frame of this study, so there is still much to be done.

FUTURE WORK

This study has tried to demonstrate that students are inconsistent in their approaches to equilibrium problems, but in doing so it has raised more questions than it has answered. The most fundamental questions are that if students are using phenomenological primitives to help them build models of situations and reach conclusions then what are these primitives and how do we determine them? There are also more accessible short term questions that may help answer the fundamental ones, such as what words or symbols serve as triggers in what situations?

The first extension of this project is the development and testing of a new concept question for equivalence that does not contain any couple symbols. Since one of the most obvious possibilities for explaining the high rate of student consideration of moment equilibrium on the equivalence question is the prevalence of couple symbols, it is desirable to test students with a question that does not contain such symbols. The question has been developed and will be tested spring 2010; it will be interesting to see if a reworked question changes the answer distribution or explanations that students give.

CONCLUSIONS

This paper has examined two sources of data, concept questions with explanations and national SCI results, to show that student approaches to equilibrium are inconsistent. The students in question completed an equilibrium question and an equivalence question, which is essentially an equilibrium question from a different perspective. Examination of students' explanations showed that only about 40% of students were consistent in their treatment of the two problems on the final exam, and comparison of the final exam explanations with answer selections implied that no more, and probably fewer, students who were included in the national SCI data were consistent in their approaches. The conclusion of this study is that when it comes to equilibrium students do not have deep-seated misconceptions that must be corrected, but that students are reacting to context, and engineering education research needs to consider different models of student behavior when confronting students' specific difficulties.

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