Surely students know this!: Patterns of error in senior engineering students problem-solving in Statics

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Abstract

This paper investigates the link between students' substance based misconceptions of force and the errors that students make in their solutions of Statics problems. The study described in this paper looked at the interviews from eight civil and mechanical engineering seniors; seven males and one female. Students were asked to think aloud as they solved problems based on the target concepts of free body diagram (FBD), equilibrium and friction. Participants' responses were analyzed using two conceptual frameworks. The first framework used in this study was from the works of Reiner, Slotta, Chi and Resnick [1] and Chi [2] and the second framework was based on the works of Steif [3]. Our findings suggest a link between students' ability to successfully solve problems in Statics and the robust nature of their misconception of force as a

material object. Findings from this study can help to uncover the misconceptions that students hold that impair their ability to successfully solve problems in Statics.

Introduction

There are several foundational concepts students are expected to draw on in order to scaffold their understanding of the concepts taught in Statics. One such foundational concept is force. It is believed that students rely on their conceptual understanding of force as a platform for subsequent learning or sense-making of concepts taught in Statics. Accordingly, failure to accurately understand the concept of force may serve to confound their understanding of associated statics concepts and in turn their ability to correctly apply these concepts to the solution of statics problems and more advanced mechanical systems.

This paper discusses a study that was designed as a step in furthering our understanding of inaccurate conceptions that students hold and how they influence students' ability to successfully solve problems. More specifically this study seeks to investigate the relationship between students' misconceptions about force and the patterns of errors that students make in their solutions to Statics problems.

Conceptual Frameworks

Two conceptual frameworks are used in this study. We will use the works of Reiner, Slotta, Chi and Resnick [1] and Chi [2] to examine the hypothesis that students think of force intuitively as a substance or a material object. Secondly, we will use the work of Steif [4] to analyze the students' solutions to Statics problems.

A large amount of research has focused on the study of students' misconceptions of abstract physics concepts in the domain of mechanics, such as light, heat, electricity and force [1, 5, 6]. In particular, these studies show that students enter into the classroom with preconceived ideas or beliefs of these abstract concepts that are derived from everyday experiences.

Hastenes, Wells and Swackhamer [5] proposed a taxonomy of misconceptions that students hold about force. As an example, students often believe that only active agents exert force and, in accordance with this notion, that rigid, unmoving objects exert no force. This example suggests that students intuitively think force is a substance, material or an object.

Studies such as Reiner, Slotta, Chi and Resnick [1] and Slotta, Chi and Joram [7] indicate that students intuitively reason about these concepts as if they are material objects or are substances. Students assign a substance-based ontology to these concepts when in essence they are process based in character [1, 2, 7]. Most students understanding of force is not consistent with the idea that a force is a process of interaction. Instead students intuitively think of force as exhibiting similar behavioral characteristics and properties of material objects. Chi [2] describes misconceptions, such as what students have of force, as stemming from students assigning an object-based ontology to a concept that is process based.

The concepts taught in Statics have their origins in the Newtonian concept of force. Consequently, during Statics instruction, students draw on their knowledge of force as a scaffold for understanding more advanced concepts in Statics [3]. A substance based conception of force is not only faulty and incompatible with Newtonian mechanics but often times resistant to traditional forms of instruction [2]. Therefore, if students rely on their substance based misconception of force as a platform for subsequent learning or sense-making this may impair or confound their understanding of associated statics concepts. During Statics problem solving, students may in turn apply their misconceptions of force to solving problems that rely on the application of Statics concepts to their solution.

Steif [4] examined the errors students make in solving Statics problems. Ten common errors were identified. Each error was shown to be indicative of one or more concepts that students failed to understand and apply accurately [8]. Steif [4] proposed a conceptual framework which highlights a set of four concept clusters considered fundamental to the analysis of engineering systems as represented in statics problems. These conceptual clusters are:

1. Forces act between bodies
2. Combinations and/or distributions of forces acting on a body are statically equivalent to a force and couple
3. Conditions of contact between bodies or types of bodies imply simplification of forces
4. Equilibrium conditions are imposed on a body

Steif [4] proposed that the source of errors that students make in solving problems in statics may stem from lapses in conceptual understanding of the four clusters of concepts. These errors and their associated conceptual lapses have been identified and are [4]:

1. Failure to show clearly in their illustration which body is being considered for equilibrium (C4)
2. Failure to treat a collection of parts as a single body, dismembering a system into its parts or dividing a part into two as needed (C4)
3. Representing a force in the FBD as acting on the body, when that force is exerted by a part which is included in the body (C1,C4)
4. Representing a force in the FBD acting on the body of the FBD, when that force does not directly act on the body (C1, C4)
5. Failure to account for the mutual nature of forces between bodies that are connected that are separated for analysis (C4, C1)
6. Ignoring a couple or falsely presuming its presence between two bodies (C2, C3).
7. Failure to account for the full range of possible forces, or to restrict sufficiently the possible forces (C2, C3)
8. Assuming a friction force is at the slipping limit when equilibrium is maintained with a friction force of lesser magnitude (C3).
9. Failure to impose balance of forces in all directions and moments about all axes (C4).
10. Contributing a couple to a force summation or not including a moment summation in a couple (C2).

If a student's conception of force plays a central role in his/her understanding of Statics concepts. Errors in the underlying structure of knowledge of force may appear as faulty conceptions in Statics which when applied to the solution of problems reveal patterns of errors.

Litzinger and his colleagues [9] studied four undergraduate students majoring in engineering who had already taken Statics. These students were asked to draw fully dimensioned free body diagrams (FBD) of the target represented in the problem statement and illustration. The intention of this study was to uncover the sources of errors that students made in their problem solutions. From this study it was found that a major source of errors in problem solving was the recall and use of conceptually erroneous knowledge in determining the solution. "When learners' prior knowledge contains inaccurate conceptions these underlying errors are passed on to the mental model that is constructed to solve a problem" [9].

The Litzinger and his colleagues study suggests that an analysis of students' solution of Statics problems may reveal patterns of errors that are reflective of consistent misconceptions that students hold [9]. The study described in this paper investigates whether there exists a significant link between students' misconceptions of force and the patterns of errors that students make in their solutions of Statics problems.

Research Questions

This paper investigates the link between students' substance based misconceptions of force and the errors that students make in their solutions of Statics problems. The research questions that guide this study are:

1. What conceptions of force do students apply to the solution of problems in Statics: substance-based, process-based, or both?
2. What are the common errors what students make when solving problems in Statics?
3. What is the relationship between students' conception of force and the common errors that they make in solving problem in Statics?

Methods

The study described in this paper looked at the interviews from eight civil and mechanical engineering seniors; seven males and one female. Seniors were used in this study because they were believed to already have mastered these fundamental concepts and also should know how to solve these problems.

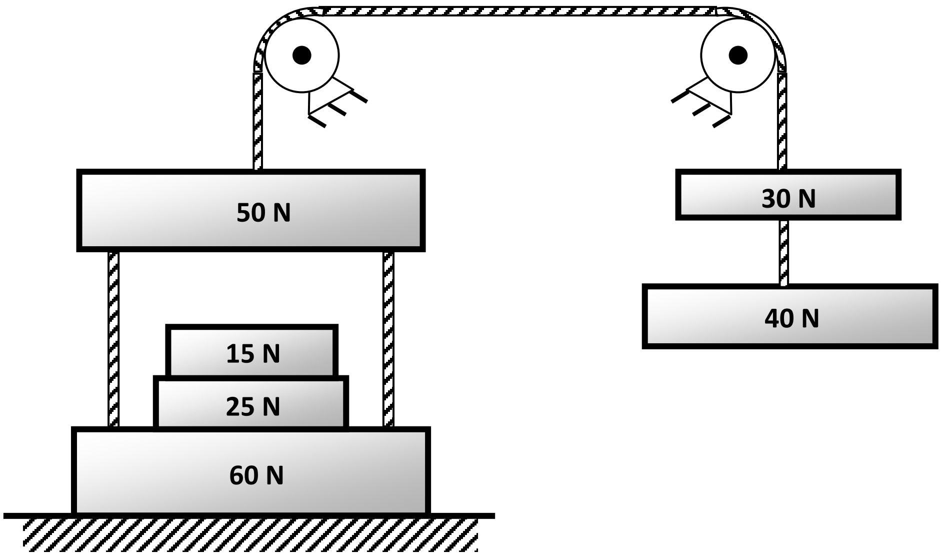
The students were asked to solve problems taken from the Statics concept inventory (SCI). Each question on the SCI was designed to target one or more misconceptions that students are believed to have in Statics. The SCI was designed to detect students' conceptual lapses through the patterns of errors that students make in their solutions [10]. These questions were given in an open-ended format rather than with the usual multiple choice options. Students were asked to think aloud as they solved problems based on the target concepts of free body diagram (FBD), equilibrium and friction. Each student completed at least one problem [11].

An example of one of the problems the students completed is shown below.

1-1 Consider the system of blocks connected by cords which wrap around pulleys. The 60 N block rests on a table.

Draw the FBD(s) required to determine the force of the table on the 60 N block.

What is this force?



Reference: Earlier version of Statics Concept Test by Paul Steif (Used with permission [12])

The transcripts were first coded for students' explanations of force as a material object or a process of interaction. A student was considered to have a robust misconception of force if their transcript for a given problem was coded three or more times for explanations of force as a material object. If the student had one or two instances of explanations of force as a material object then their misconception of force was considered less robust. If their explanations were unclear their explanations were coded as indeterminate. .

The second step in the analysis was to identify which of the three concepts were being tested in the problem and therefore central to the problem solution. All the student errors in their FBD, calculations and explanations were then coded and categorized according to the concept(s) that they failed to represent correctly. The intent of this analysis was to first determine if students made similar errors on a given problem; secondly, to determine whether these errors could be categorized according to the ten common errors. Thirdly, to determine if all the errors that students made for a given problem solution represented the Statics concept(s) that were being tested in the problem.

Results

The results from this analysis were used to determine if there were any patterns or link between students' substance based conception of force, the mental models constructed to solve problems (FBD), their calculations, their explanations and the accuracy of the solutions that they generate.

1. What conceptions of force do students apply to the solution of problems in Statics: substance-based, process-based, or both?

Phrases such as "taken off" were coded as indicating that the student talks about force as though it is an object or substance. In the excerpt shown below the student's explanation was coded to mean that the student sees force as existing in the rope because of the weights attached to the rope. Similar verbiage to "force is being taken off" such as "force on the rope" indicated a similar way of thinking of force as within or on the rope. Examples of excerpts that were coded as substance-based are:

"Trying to combine all the weights and all the--the tensions to get an idea of how much force is being taken off of the left-hand side of the system."

"Not necessarily an equation that describes what tension is. But, there's a force on each of the cords here that makes it so they don't tear apart. But yet, they're having to hold up whatever block that they're attached to."

"Yeah. So the total is 90 newtons, and it's going to tension half and half into here. I assume this is balanced."

Analysis of students interview protocols indicate that all of these students sometimes talk about force as a direct casual process. Only one of students got the answer correct to the question that dealt with equilibrium and FBD. This student also spoke of force as a substance. An example of his explanations of force is:

"So that would be an inequitable force of 20 newtons going up, on the rope. Ten on each rope. And then, this total weight pulling down, I'd subtract it too."

These data of students' explanations of their problem solving processes indicate that students have a substance-based conception of force. Furthermore, the data suggest that students who showed evidence of having a substance-based conception of force could still succeed at solving problems relating to force.

2. What are the common errors what students make when solving problems in Statics?

An analysis of the student interviews indicated that students who got the answer incorrect showed patterns of errors in their solutions that represented misconceptions about the target concept. Evidence of these common errors were identified in students' FBD, calculations and explanations of their problem solving processes. The following list of errors was found within incorrect solutions to the problem that tested the concept of equilibrium. They are:

1. Failure to show clearly in their illustration which body is being considered for equilibrium

2. Failure to treat a collection of parts as a single body, dismembering a system into its parts or dividing a part into two as needed
3. Representing a force in the FBD as acting on the body, when that force is exerted by a part which is included in the body
4. Representing a force in the FBD acting on the body of the FBD, when that force does not directly act on the body
5. Failure to account for the mutual nature of forces between bodies that are connected that are separated for analysis
6. Failure to impose balance of forces in all directions and moments about all axes.

All these errors are associated with a misunderstanding of the concept of equilibrium according to Steif's framework [4]. Among students who got the answer incorrect there was no common error found in their solution.

Josh and Nicki were the two students who got the answer to the SCI question that targeted students' misconception of FBD, equilibrium and friction incorrect. Analysis of their interviews uncovered the following patterns of errors.

1. Assuming a friction force is at the slipping limit when equilibrium is maintained with a friction force of lesser magnitude.
2. Failure to impose balance of forces in all directions and moments about all axes (C4).
3. Representing a force in the FBD as acting on the body, when that force is exerted by a part which is included in the body
4. Representing a force in the FBD acting on the body of the FBD, when that force does not directly act on the body
5. Failure to account for the mutual nature of forces between bodies that are connected that are separated for analysis

All these errors are associated with a misunderstanding of all three concepts according to Steif's framework [4]. Among students who got the answer incorrect there was no common error found in their solution.

3. What is the relationship between students' conception of force and the common errors that they make in solving problem in Statics?

Students who used verbiage that indicated a substance-based conception of force more than once were coded as having a robust misconception of force. Students transcripts that did not show any common errors in their solution that was associated with the concept being targeted in the question were coded as having not having a misconception of the target concept. The results are summarized in Table 1 below.

Table 1. Summary of Results

Question	Student Pseudonym	Misconception of Force	Target Concept	Solution
1	Johnny	Robust	Incorrect	Incorrect
3	Johnny	Robust	Incorrect	Incorrect
2	Josh	Indeterminate	Incorrect	Incorrect
3	Josh	Less Robust	Correct	Correct
2	Mike	Less Robust	Correct	Correct
3	Mike	Less Robust	Correct	Correct
1	Harry	Robust	Incorrect	Incorrect
1	Jerome	Robust	Incorrect	Incorrect
1	Tony	Less Robust	Correct	Correct
2	Nicki	Robust	Incorrect	Incorrect
2	Mille	Less Robust	Correct	Correct

Students who got the answer incorrect showed errors in their FBD, their calculations and their explanations of their problem solving processes that reflect misconceptions about the target Statics concepts. These students showed evidence of having a robust misconception of force as a material object when compared to their peers who got the answer correct.

Solutions of students who got the answers correct were not free of conceptual errors. They also talked about force as a material object but their misconception was less robust when compared to their peers who got the answer incorrect. There was no evidence in their FBD, their calculations and their explanations of their problem solving processes to show that these students had misconceptions about the target Statics concepts being tested in the problem.

Conclusions and Significance

Students made errors in their FBD, calculations and explanations of their problem solutions when solving Statics problem. Each error represented one or more misconception(s). Students who made the common errors associated with the concepts being targeted in the problem got the answer incorrect in the end. These results suggest that they do not accurately or fully understand the given concepts i.e., they have misconceptions about the concepts of FBD, equilibrium and/or friction. These results were typical among students who produced inaccurate solutions.

These findings suggest that the ten common errors [10] represent students' misconceptions of Statics concepts. Instructors can, therefore, consider applying the framework - of the common errors and the conceptual lapses that they represent - to assessing students' solutions to Statics problems. Assessing students' problem solutions in this manner can provide information on the misconceptions that students may still have after instruction. This information can be used to provide pedagogical feedback to the instructor, formative assessment to the student, and/or summative assessment of students' learning gains at the end of the Statics course.

All students explained their problem solutions by describing force as a material object. The findings of the study presented in this paper suggest that students have a substance-based conception of force that is prevalent and counter-productive to successful problem solving. Slotta and Chi [13] studied whether these substance-based misconceptions can be corrected or repaired through a two step instructional approach. The first step is to teach students about the fundamental characteristics and aspects of emergent processes and engage the students in thinking and reasoning about those attributes. Secondly, to instruct students in the targeted scientific concept by focusing on the process-based nature of the concept and avoiding language, analogies or phenomena that represent a substance based view. Slotta and Chi [13] found that students are unable to correct or repair their misconceptions until they learned to reason and think about the scientific concept as a process. More importantly, their findings suggest that conceptual change can be facilitated in students using this two step instructional approach.

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