AC 2008-402: IDENTIFYING AND REMEDIATING DEFICIENCIES IN PROBLEM-SOLVING IN STATICS

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Identifying and Remediating Difficulties with Problem-solving in Statics

Abstract

The work described in this paper is part of a multi-year study that seeks to enhance students' ability to create 'models' successfully as they solve problems in Statics. The ultimate goal of the study is to understand the major difficulties that students encounter as they learn to model during problem-solving in Statics and to create interventions to help them more quickly overcome those difficulties. In the first phase of the study, more than 300 students completed three inventories: math skills, spatial reasoning and statics concepts. The results from the inventories were used to identify clusters of students with common characteristics, and therefore, presumably common deficiencies in their problem solving in Statics. Students from each cluster were then invited to participate in think-aloud problem solving sessions to identify the weaknesses in their problem solving. Analysis of the think-aloud sessions identified a number of common issues in students' knowledge and ability to create models, which are summarized in the paper. Based on these findings, the research team identified possible interventions to address the common issues. Two of these interventions were developed through a design experiments process in which they were tested with groups of up to 30 students, refined to enhance their effectiveness, and then re-tested. The interventions and the development process are described, and results from the final round of the design experiments are presented.

Introduction

The work described in this paper is part of an on-going study of problem solving in Statics. [1,2] The work is being done in Statics classes because it is one of the first places that engineering students encounter the engineering problem-solving process. In this study we are paying particular attention to the early steps in problem-solving when students 'model' the system being studied to create a set of equations describing the system. In Statics students typically read a problem statement and then create a model of the system, the free-body diagram, which contains all of the salient forces on the body. Then, based on the free-body diagram, they create a mathematical model of the system.

The current phase of the work is aimed at answering two main questions about the modeling processes: What are the major difficulties that students encounter when they perform modeling during problem-solving? What instructional interventions will address these problems and improve engineering students' modeling during problem-solving? In the current phase of the work, interventions that are developed will be tested in a full-scale experimental design.

Clearly there are many different ways in which students can go wrong as they solve problems in Statics. They may, for example, have inadequate knowledge of the forces and moments for particular types of connections, an inability to visualize forces, or inadequate math skills. Our working hypothesis is that students will cluster into different groups based on their abilities and knowledge, and that these groups will demonstrate differing abilities to solve Statics problems.

Therefore, improving the problem-solving skills of these groups will require different interventions.

The work described in this paper includes the identification of the major difficulties students encounter and the development of interventions to address some of those difficulties. In addition, results of an analysis to identify clusters are presented and used in the interpretation of the results obtained during the development of the interventions.

Relationship to Previous Work

This study has been influenced by a number of studies of problem-solving in general and of problem-solving in engineering specifically. The relationship to past work was discussed at some length in a previous paper[2] and, therefore, it is only briefly summarized here. Three subsets of the literature have had the most influence on our work: Problem-solving processes, domain knowledge, and translations between symbol systems.

Since Polya's seminal work in mathematics,[3] the utility of learning and using a sequence of steps during problem-solving has been widely accepted. Although several specific models exist, a generic 4-step model captures most: (1) Represent the Problem, (2) Goal Setting and Planning, (3) Execute the Plan, and (4) Evaluate the Solution. In the first step, problem representation, the student must read the problem statement and discern the objective. There are instructional interventions for engineering education that are grounded in this theoretical model of problem-solving. For example, Gray *et al.*[4] developed a systematic approach to solving Statics and Dynamics problems. In this intervention, it is recommended that students be taught the sequence of: Road Map (Planning), Modeling (Representation), Governing Equations (Representation), Computation (Execution), and Discussion and Verification (Evaluation). Don Woods completed some of the most thorough work that has been done in this area while developing the McMaster Problem-solving program.[5] In his most recent work,[6] Woods has focused on the processes of problem-solving and has developed a model to describe ideal problem-solving.

Without a doubt, the quantity of prior domain knowledge affects problem-solving.[7] It is also widely accepted that qualitative aspects of knowledge matter. Prior knowledge is believed to act as an important scaffold for problem-solving. The structure provided by the knowledge base can, for example, act as a constraint during analogical reasoning,[8] support strategic processing during reading,[9] and contribute to positive motivational states during problem-solving.[10] In short, the effects of prior knowledge are wide-reaching and powerful. Within the domain of Statics, Paul Steif closely examined the role of misconceptions[11] and developed a concept inventory in collaboration with Dantzler[12] to determine the effect of these misconceptions on problem-solving. Mehta and Danielson have developed and used a Statics skills and knowledge inventory.[13, 14]

The third approach to understanding problem-solving in engineering focuses on the symbol system translations inherent in the analysis process. By symbol system, we refer to the semiotic system used to understand and express elements and their relations. Mathematical expressions are an example of a semiotic system in which numbers and operators act as elements. How these elements are configured in relation to one another communicates the full meaning of the expression. Translations are required when problem solvers move between symbol systems. McCracken and Newstetter[15] developed the Text-Diagram-Symbol (TDS) model to capture the transformations that take place during analysis. This model includes verbal (Text), visual (Diagram), and mathematical (Symbol) semiotic systems through which the student must pass to complete an analysis task, with each phase corresponding to a different symbol system. The importance of visualization in transforming from a problem statement to a free-body diagram and the well documented gender effects on visualization skills, see for example,[16, 17, 18,] led us to include spatial reasoning instruments in the study.

Methodology

In order to identify clusters of students, data were collected on three types of measures: mathematics, spatial reasoning and conceptual knowledge related to Statics. A secure web site was created to provide participants with easy access to the measures. Upon completion and testing of the website, participants were recruited from Statics classes. Participants were offered extra credit on their course grade for the completion of the measures. Students were able to log in and out of the web site, enabling them to take the three measures in any order and in multiple sittings if desired. During their first visit to the website, students were asked to read and indicate agreement with the informed consent and also to answer basic demographics questions, such as gender, race, SAT scores, major, and GPA. They then were brought to a new page containing a separate link to each measure.

Ward's method of cluster analysis[19] was applied to the data to identify clusters whose members performed similarly on the measures. Ward's method forms groups by considering all possible pairs of participants, seeing which set has the least difference in their set of responses. After the first group is created, the mean of their responses are considered one group, and all possible sets are again considered. This iterative process is repeated until all participants are combined in one group. In the method used, the squared Euclidean distances are the measure of the differences between the groups. Participants are grouped so that within-group differences are minimized and differences between groups are maximized. The analysis was conducted with SPSS 14.0.

In the first round of the data collection, which took place during Fall 2006, the cluster analysis was followed by selection of students for think-aloud sessions. Thirty-nine students were randomly selected across the clusters to participate in one-on-one sessions that included think-aloud problem solving and discussion of items from the Statics Concept Inventory that were identified as discriminating well across the clusters. The think-aloud problems asked the students to create a free-body diagram and the corresponding set of equilibrium equations. In addition, students were asked qualitative questions about their problem solving in Statics. Data from these interviews was analyzed by a team of six expert instructors to identify key difficulties across the clusters.

Based on the key difficulties that were identified, a cross-functional team of experts from engineering and educational psychology worked to create and refine two interventions through a series of 'design experiments.' The goal of the design process was to create 'materials-driven' interventions that would be done by students outside of the classroom without interaction with the instructor or teaching assistant. In order to assess the effectiveness of the interventions, a short pre/post-test was created. This test was also refined throughout the series of design experiments. Descriptions of the interventions and the pre/post-test are included in the discussion of the results.

After initial design of the interventions, three rounds of design experiments were undertaken; the design experiments sequence is summarized in Table 1. With each round, the number of students per session was increased. In addition the sessions were increasingly less dependent on the presence of a content expert. The focus of the first round of data collection was to pilot the materials and session process. Ten sessions were offered with three to five students attending per session. A content area expert first distributed a pretest to students. Upon completion of the pretest, intervention materials were given to the students. Each student worked individually on problems, one at a time. After the problem was completed by all students in the group, the content expert used a blackboard to discuss the correct response. This solve/discuss process was repeated several times depending on the intervention received until the intervention was complete. At the conclusion of the intervention, a post-test was delivered. Once all students were finished with the post-test, students were asked to offer their opinions of the session. Recommendations made by students addressed the instructions of the problems, organization of the session, benefits of the session, and the problem types given in the session.

Table 1. Sequence of design experiments

	Design Exp I	**Design Exp II**	**Design Exp III**
Group size	3 to 5	15 to 30	15 to 30
Location	Conference room	Computer lab	Testing center
Pre-test	Paper	Computer-based	Computer-based
Interventions	Paper	Computer-based	Computer-based
Expert solutions	Live discussion	Live discussion	Voice annotated solution (headphones were provided) Written solution
Post-test	Paper	Computer-based	Computer-based

The information gleaned from the first session led to modification of the instructions to the problems to enhance students' understanding of the questions and what was being asked of them. The second session was reformatted to be electronically administered within an on-line course management system. Six sessions were held in the second round, each accommodating 15-30 students. The pretest, post-test, and all intervention problems were administered electronically. Administration ensured all students worked on a particular section at a certain time. When the content expert reviewed the correct answers to the questions on the blackboard, all students in the session remained on the same question. At the end of the session, students again discussed the session and made comments about the session.

For Round 3 of the design experiments, all questions on one of the interventions were modified to include multiple choice answers that permitted automatic scoring. Also a list of justifications for the force and couple reactions was added to one of the items in the pre/post-test. The list of justifications included incorrect answers that were based on student responses from Round 2.

This change was made in an attempt to extract more information about the effects of the interventions from the pre/post-test results. The other major change was the movement to a delivery that included no interactions with the content expert.

In Round 3, students went to a testing center at a time convenient to them and individually completed the session at their own pace. The session was delivered in the same course management system as in Round 2. To make the sessions entirely independent of the interactions with a content expert, short videos (~ 1 minute) of the content expert reviewing the correct response to the questions were created using CamStudio software. The videos showed the same problem given to the student and displayed the same writing that the content expert used on the blackboard in Rounds 1 and 2. The audio recording was also the same as that given during round one and two when the content expert reviewed each problem. In addition to these short videos, students also had access to an image of the final solution with a written description of how the problem was completed, comparable to the audio portion of the video. This was done to ensure that students were given two mediums for receiving the solution to the problem, in addition to accommodating students with hearing difficulties, and as a backup in the event of technical difficulties. Students progressed through the session completing the pretest, the intervention questions with the videos following each question, and the post-test. A textbox was available for students who wished to make comments about the sessions.

During Fall 2007 a second data collection process for cluster analysis was also undertaken. The results of the cluster analysis were used to assist in the interpretation of the results from the interventions and the pre/post-testing. The cluster analysis results were also used to select high and low performing students whose answers on the interventions were reviewed in detail.

Cluster Analysis Measures

Two mathematics measures were used in the cluster analyses done in Fall 2006 and Fall 2007. The 2006 study used a mathematics test consisting of the ten math questions from the inventory developed by the Mehta and Danielson,[13] which is intended to measure students' knowledge of the prerequisite mathematics for a Statics course. Problems include solving basic equations for one- and two-variables, finding triangle characteristics through trigonometry and similarity, basic integration, and vector multiplication. Analysis of the resulting data showed that the students did so well on the ten items that the scores provided little discrimination among the students. Consequently a new mathematics test was created by the investigators and utilized for the Fall 2007 study. The new mathematics baseline measure consisted of a smaller subset of relevant questions in the original mathematics baseline measure. Five items with a high degree of discrimination as well as items directly pertaining to trigonometry were selected from the original battery. An additional five items were created by the research team on the subject of equivalent angles, use of trig functions, and magnitude of vectors and scalars.

Spatial reasoning was assessed by two well-accepted measures in the field, Card Rotation and Paper Folding from the Factor-Referenced Cognitive Tests.[20] Both tests are timed, limiting the students to three minutes for each set of items (12 minutes total). The original tests were developed in paper and pencil format and were adapted for online use. The online versions were designed to be as much like the paper and pencil version as is possible. In the Card Rotation task, participants are asked to observe a target image, then determine whether eight other images are planar rotations of the figure, or other transformations such as mirror-image. Students indicate which of the images are equivalent to the original image. Scores are assigned by subtracting the number of incorrect responses from correct responses. The reported reliability for this measure is 0.8020; the reliability for our delivery was 0.97. In the Paper Folding task, a series of two to four folds are indicated through diagram, and various holes are punched into the folded paper. Participants are to choose which of five options has the correct hole configuration on the unfolded piece of paper. This score is found by awarding one point for an accurate response, and subtracting ¼ point for an incorrect response. The reported reliability for this measure is 0.8420; the reliability for our delivery was 0.72

Knowledge related to Statics was measured using the Statics Concept Inventory,[12, 21] which is a 27-item measure of the concepts that have been identified as key in Statics comprehension. The inventory is intended to only tap conceptual errors, so very little math is involved, and what math is used is trivial. The inventory measures nine areas of conceptual understanding, forces on collection of bodies, Newton's 3rd law, Static equivalence, roller forces, slot forces, negligible friction, representation, friction, and equilibrium. The reported reliability of this test is 0.83 for students who have completed a Statics class.[21] The reliability for the administration of the test in this study, which occurred midway through the Statics course, was 0.70.

Samples for Cluster Analysis and Design Experiments

During data collection in Fall of 2007, 390 of the 560 students enrolled in Statics completed all three measures. However, two students provided invalid SAT scores and were eliminated from the sample, leaving a total of 388 students for the cluster analysis. Because testing was done in an online environment, the reasons some students did not complete all measures could not be determined. The demographic characteristics of the participants who completed all the measures are summarized in Table 2. The majority of the participants were white (87%), male (85%), and sophomores (88%). The participants had an average SAT verbal score of 571, and SAT math score of 648 (all self-report).

Table 2. Sample demographics for Cluster Analysis

	Count	**Percent**		**Count**	**Percent**
Gender			**Ethnicity**		
Male	329	85	African-American	9	2.3
Female	59	15	Arab	7	1.8
			Asian	12	3.1
Year in School			Caucasian	339	87.4
Freshman	2	0.5	Hispanic	8	2.1
Sophomore	340	87.6	Indian	7	1.8
Junior	41	10.6	Pacific Islander	0	0.0
Senior	5	1.3	Other	6	1.5

A total of 233 students chose to participate in the design experiments process; all received extra course credit for participating. Some of these students, however, had not completed the inventories used in the cluster analysis. Therefore, only 164 students completed the inventories and participated in the design experiments process. A comparison of the scores of the 164 students to the entire sample that completed the inventories showed that the two groups were equivalent.

Results and Discussion

Analysis of the videos of the think-aloud problem solving and discussion questions was done by the team of six experts during Fall of 2006. The experts included five faculty members in Engineering Mechanics/Mechanical Engineering and one Ph. D. candidate in Engineering Mechanics, who has been an instructor of mechanics courses for five years. This same team also scored the students' written work from the sessions. The major difficulties in problem solving identified through the analysis of the think-aloud videos and student work were:

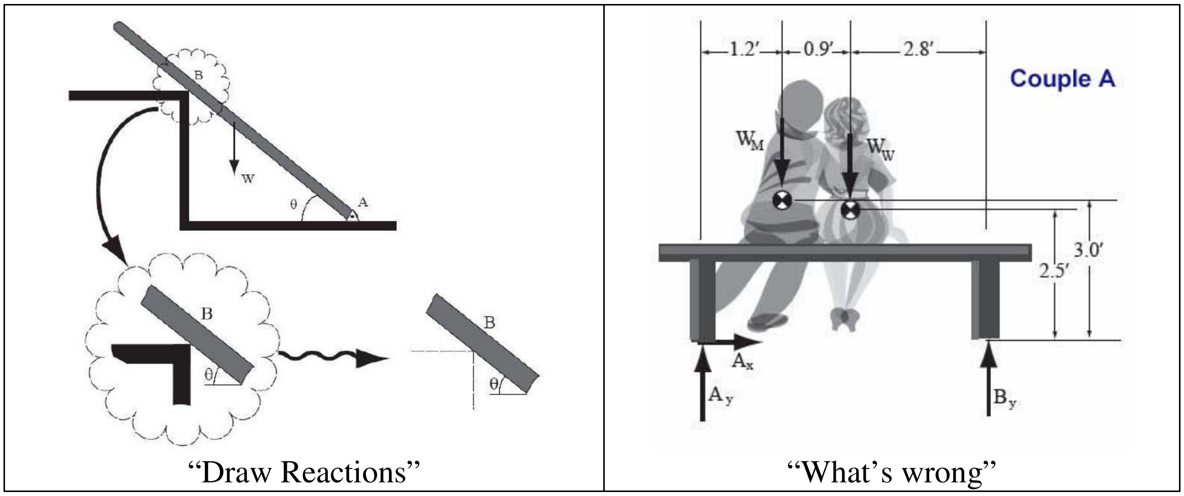
- Students did not grasp fully the concept of a free-body diagram including the distinction between internal and external forces.
- Students relied mostly on memory to decide what reactions to include based on the type of connection/interaction.
- Students did not have a physical understanding of the reactions that could be supported by different types of connections/interactions between bodies.
- Students often failed to include a moment equation in their equilibrium equation set.
- Some students had significant difficulty with trigonometry.

Based on the results of the analysis of students' work and the videos, the research team identified the following possible interventions:

1. Draw the reactions at given connection/interaction and explain why those reactions exist
2. Analyze a given free-body diagram and identify whether the reactions shown are correct or not and justify analysis with physical reasoning
3. Draw free-body diagrams for actual objects and justify reactions with physical reasoning
4. Draw reactions at a given type of support embedded within a series of increasingly complex bodies
5. Use a list of detailed instructions on creation of the FBD, provided by the instructor
6. Manipulate model connections/interactions to build physical understanding
7. Equilibrium equations intervention
8. Remedial trigonometry module

The team focused on the first two interventions during Fall 2007 because properly identifying reactions is absolutely critical to creating an accurate free-body diagram. Some work was also done on intervention 3. However, writing problems involving actual objects that were challenging but did not require lengthy explanation proved to be difficult, so work on intervention 3 was halted. For both interventions 1 and 2, students were asked to explain their answers, which required them to undertake a process of 'elaboration' that has been identified as one approach to increasing conceptual understanding.[22] Representative problems from the two interventions are presented in Figure 1. The two types of interventions were given the short-names "Draw reactions" and "What's wrong," which will be used in the remainder of this paper to refer to the interventions.

A five item pre/post-test was also developed through the design experiments process. The items included two questions on reactions, two questions on free-body diagrams and one on a moment equation. In the five items students were asked to select the correct answer. During the second round of the design experiments students were asked to type justifications for their answers to two of the items. In the final round of design experiments, one of the items involving reactions was modified to include a list of justifications that included distracters based on student responses to Round 2 interventions.



"Draw Reactions"

"What's wrong"

Figure 1. Representative images from the interventions

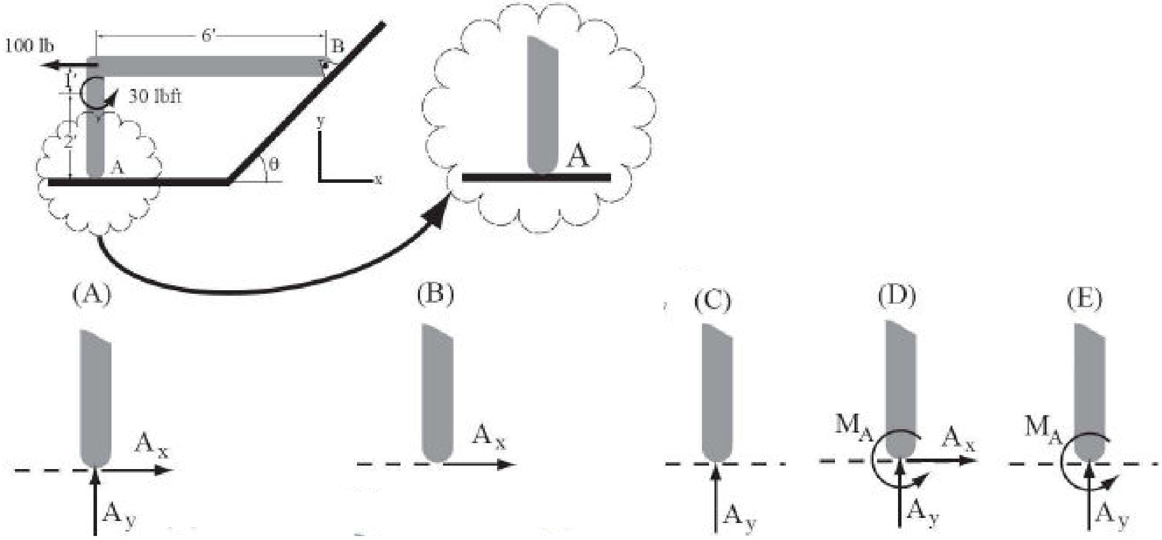


Figure 2. Problem figure and answers for Question 5 on the pre/post-test

Table 3 presents a summary of the multiple choice answers from the pre-test. Not all students provided answers to each item so the total number of students varies across the items. Ideally the all students would get all of these items correct. The data shows that the fraction of correct responses ranges from 62% for Question 3 on a pin in a slot to 89% for the moment equation item.

Table 3. Results from pre-test in Round 3 of design experiments

	FBD with pin and smooth point contact	Moment eqn. for FBD of body with roller and pin	Reactions for pin in slot	FBD with roller and pin	Reactions at smooth point contact
	Q1	Q2	Q3	Q4	Question 5
A	3	**197**	**136**	**173**	35
B	**189**	6	29	14	1
C	18	6	29	23	**161**
D	11	12	27	4	6
E	NA	NA	NA	NA	12
% correct	86%	89%	62%	81%	75%

Question 5 included justification statements for the couple reaction as well as x and y-reaction forces; Figure 2 presents the drawing that was used in Question 5. Students were asked to select as many statements from the list as they felt were necessary to justify the answer that they selected. Table 4 presents a summary of these results for each reaction. The results show that the fraction of students selecting correct reasoning for the couple and x-reactions is less than the 75% that selected the correct free-body diagram. In contrast, the correct justification for the y-reaction was selected by 96% of the students. The total number of students who selected a justification for the y-reaction is substantially smaller than for the couple or x-reaction. The smaller number of selections for the y-reaction justification may indicate that many students did not take the time to read carefully through the entire list, which had nine elements with the y-reaction responses listed last.

In order to get Question 5 completely correct, students had to select the correct free-body diagram and only the correct justifications. Out of the 215 students who gave meaningful responses to Question 5 only 29 got the question completely correct. Thus, of the 161 students who selected the correct answer to Question 5, only about 1 in 5 could fully justify their answer when selecting from a list of justifications. Given the large number of students who failed to select a justification statement for the y-reaction, the number of students who selected the correct answer and the correct justifications for the couple and x-reaction, but did not select either justification for the y-reaction, was also determined. There were an additional 19 students in this category.

Table 4. Justification selections for Question 5 of pre-test

Reaction	Justification statement	N	% correct
Couple	There can be no reaction couple because the bar is free to rotate about point A	118	57%
	There may be a reaction couple because the bar is free to rotate about point A	13	
	There can be no reaction couple because the surface is smooth	77	
		Total=208	
X-reaction	There can be no x-reaction force at point A because friction is irrelevant due to the pin at point B	28	
	There can be no x-reaction force at point A because the contact is smooth.	143	65%
	There can be no x-reaction force at point A because the pin at point B prevents it from moving in that direction	34	
	There may be an x-reaction force at point A because there must be a reaction to the horizontal 100 lb load.	15	
		Total=220	
Y-reaction	There can be no y-reaction force at point A because there is no vertical load of the bar	5	
	There may be a y-reaction force at point A because the contact can resist motion in the y-direction	107	96%
		Total=112	

Table 5 presents the success rate of students on the Draw Reactions intervention for the reaction forces and couples as well as the fraction of students who identified both the force and couple reaction correctly. The performance on the rigid and pin connections, which the students encounter explicitly in the textbook and in class, is acceptable. However, for the bar resting on a corner, the success rate for the reaction forces is quite low indicating that the students cannot correctly reason through this problem.

Table 5. Fraction of correct responses for Draw Reactions Intervention (N=215)

	Rigid connection	**Pin connection**	**Bar resting on corner**
	DRQ1	DRQ2	DRQ3
Reaction forces	82%	93%	50%
Reaction couple	78%	84%	88%
Both correct	71%	80%	46%

To gain more insight into students' reasoning on the Draw Reactions problems, the justifications written by a sample of students from high and low performing clusters were evaluated. The overall characteristics of the students in the clusters are presented in Table 6. With the exception of the card rotation score, means of all inventories increase monotonically with cluster rank. Interestingly the best performing cluster, cluster 5, has a greater fraction of female students than any other cluster.

The performance of male and female students on the inventories was equivalent except for the Statics Concept Inventory. The data from Fall 2006 showed that the female students had a lower average score than the males. The same trend exists in the Fall of 2007 data. Analysis of the combined data sets shows that the difference is statistically significant. The average score for male students was 10.5 and the average for the female students was 9.1 (F=12.25, $p<0.001$)

Table 6. Summary of characteristics of clusters in 5-cluster solution

	Range of scores	**Cluster 1** N=32	**Cluster 2** N=90	**Cluster 3** N=123	**Cluster 4** N=119	**Cluster 5** N=24
Math	4 to 15	11.2	11.7	12.0	12.6	12.7
Statics concept	2 to 21	8.9	9.4	10.1	10.9	11.8
Card rotation	29 to 160	95	116	102	111	109)
Paper folding	2 to 36	20.8	24.3	24.5	25.8	27.5
SAT	840 to 1500	1006	1130	1213	1310	1427
% Female	NA	16%	16%	12%	15%	29%

The justification statements from representative students from high and low performing clusters were reviewed by a two pairs of content experts. The experts agreed upon a scoring approach prior to the evaluating the justifications. The scoring grid included six categories, four for incorrect justifications and two for correct justifications. A category of 'effectively no explanation' was used for a statement such as "there are both x and y-reactions because it is a pin connection." Such answers did not reveal anything about the student's understanding of the motions permitted by a connection and their relationship to the possible reactions. This type of answer suggests that students were working from memory rather than reasoning. Other categories in the scoring grid included answers that were incorrect because the student mistakenly included effects of loading or other connections in their justification. A third category included incorrect arguments based on possible motions, but which were offered in support of an incorrect answer.

In order to assess the quality of justifications for the Draw Reaction intervention, the justifications from students in high and low performing clusters were analyzed. The data set available limited the number of students in the high and low performing groups to nine. Each student completed three items that included justification for the reaction forces and couples. So the total number of justifications reviewed was 54 for each group. The totals in the tables are not 54 because a few justifications did not fit any category, and in other cases the justification fell into more than one category. Tables 7 and 8 present the results of the analysis for students from the low and high performing clusters, respectively. The overall fraction of correct responses in the two groups is approximately the same, 72% versus 60%. However, students in the high performing clusters were much more likely to provide correct reasoning and much less likely to offer justifications that suggested that they were relying on memory.

Table 7. Analysis of justification statements for Draw Reactions intervention by students sampled from low performing clusters (N=9 students; total of 54 justification statements)

	Incorrect: influenced by loading	**Incorrect:** influenced by other supports	**Incorrect:** based on possible motion	**Incorrect:** effectively no explanation (memory)	**Correct:** based on possible motion	**Correct:** effectively no explanation (memory)
Reaction forces	1	1	2	7	7	9
Reaction couple	1	2	2	2	10	9
% total	4%	6%	8%	17%	32%	34%

Table 8. Analysis of justification statements for Draw Reactions intervention by students sampled from best performing clusters (N=9 students; total of 54 justification statements)

	Incorrect: influenced by loading	**Incorrect:** influenced by other supports	**Incorrect:** based on possible motion	**Incorrect:** effectively no explanation (memory)	**Correct:** based on possible motion	**Correct:** effectively no explanation (memory)
Reaction forces	4	2	2	2	14	5
Reaction couple	1	3	1	1	21	2
% total	9%	9%	5%	5%	60%	12%

The What's Wrong intervention did not have a multiple choice structure so students provided only written answers and justifications for those answers. To date the work of only a small sample of students has been analyzed using the same scoring grid that was used for the Draw Reactions interventions discussed above. It is important to note that this student sample was distinct from that analyzed for the Draw Reactions interventions because each student completed only one of the two types of interventions. The results, presented in Tables 9 and 10, show no difference in the accuracy of the justifications written by the two groups of students. Thus this data sample indicates that cluster rank had no effect on performance, in contrast to the results from the Draw Reaction interventions in which the students in the higher clusters performed better.

Table 9. Analysis of justification statements for "What's Wrong" intervention by student sample from worst performing clusters

	Incorrect: influenced by loading	**Incorrect:** influenced by other supports	**Incorrect:** based on possible motion	**Incorrect:** effectively no explanation (memory)	**Correct:** based on possible motion	**Correct:** effectively no explanation (memory)
Reaction forces	5	7	1	3	5	34
Reaction couple	0	0	2	8	7	34
% of total	5%	7%	3%	10%	11%	64%

Table 10. Analysis of justification statements for “What’s Wrong” intervention by student sample from best performing clusters

	Incorrect: influenced by loading	**Incorrect:** influenced by other supports	**Incorrect:** based on possible motion	**Incorrect:** effectively no explanation (memory)	**Correct:** based on possible motion	**Correct:** effectively no explanation (memory)
Reaction forces	0	0	0	10	6	32
Reaction couple	4	0	0	4	4	36
% of total	4%	0%	0%	15%	10%	71%

Tables 11 and 12 present post-test results in the same format as Tables 3 and 4. A comparison of the corresponding tables shows that the interventions did not have a significant effect on students’ ability to answer the questions correctly or to select correct justifications for Question 5. However, a check of the number of students who got Question 5 fully correct showed an increase from 29 to 38 – a small positive sign. Among these students, 12 students who had the correct answer but incorrect justifications got the item fully correct on the post-test, and 6 who had the incorrect answer and incorrect justifications got the item fully correct on the post-test. Twenty students got Question 5 fully correct on the pre and post-test. Nine students who had gotten Question 5 fully correct on the pre-test selected incorrect justifications on the post-test.

Table 11. Results from post-test in Round 3 of design experiments

	FBD with pin and smooth point contact	Moment eqn. for FBD of body with roller and pin	Reactions for pin in slot	FBD with roller and pin	Reactions at smooth point contact
	Q1	Q2	Q3	Q4	Question 5
A	7	**198**	**152**	**171**	30
B	**188**	4	22	20	0
C	20	5	25	18	**154**
D	5	13	21	3	19
E	NA	NA	NA	NA	12
% correct	85%	90%	69%	81%	72%
% changed answers	16%	5%	29%	19%	28%

Table 12. Justification selections for Question 5 of post-test

Reaction	Justification statement	N	% correct
Couple	There can be no reaction couple because the bar is free to rotate about point A	118	57%
	There may be a reaction couple because the bar is free to rotate about point A	13	
	There can be no reaction couple because the surface is smooth	77	
		Total=204	
X-reaction	There can be no x-reaction force at point A because friction is irrelevant due to the pin at point B	28	
	There can be no x-reaction force at point A because the contact is smooth.	143	69%
	There can be no x-reaction force at point A because the pin at point B prevents it from moving in that direction	34	
	There may be an x-reaction force at point A because there must be a reaction to the horizontal 100 lb load.	15	
		Total=219	
Y-reaction	There can be no y-reaction force at point A because there is no vertical load of the bar	5	
	There may be a y-reaction force at point A because the contact can resist motion in the y-direction	107	99%
		Total=123	

Summary

The process of identifying student difficulties through the think-aloud problem solving and interviews pointed to key problems that cut across most of the clusters. The most fundamental of the difficulties related to reactions at connections and construction of accurate free-body diagrams were selected for development of instructional interventions. The analysis of small samples of student justification statements showed mixed support for our working hypothesis that students in different clusters will need different interventions. The data from the Draw Reactions intervention indicated better performance by students in the higher rank clusters, whereas the results from the What's Wrong intervention showed no difference. We are continuing to do analysis to establish more completely the significance of the clusters for design of the interventions.

The results presented here cannot support conclusions on the overall effectiveness of the interventions, which will have to wait for full-scale testing in Fall of 2008. However, the results do indicate that the process of design experiments was successful in developing materials-driven interventions with the potential to improve student performance. Even so, work to enhance the interventions and the pre/post-test will continue. The analysis of student responses suggests improvements should be made in the structure of the pre/post-test to eliminate problems such as the low fraction of students who chose justifications for the y-reaction in Question 5 of the pre/post-test. Further work will also be required to enhance the reliability of the pre/post-test. In addition, the number of intervention problems will be increased to provide more practice for students.

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