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Validating the Diagnostic Capability of the Concept Assessment Tool for Statics (CATS) with Student Think-Alouds

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Abstract

This paper reports findings from a verbal protocol study eliciting students' reasoning about key statics concepts as assessed by the Concept Assessment Tool for Statics (CATS). The work is part of a larger project focused on developing a comprehensive model of validity for the use of concept inventories in engineering education. The interviews collected and analyzed as part of this study provide validity evidence regarding the concepts assessed and the nature of student reasoning in solving statics problems. Findings suggest that CATS can provide evidence for instructors as to whether or not students have attained mastery of specific concepts. However, aspects of the data reveal that there is ambiguous evidence regarding the nature of students' mastery of specific concepts.

Introduction

Engineering concept inventories have the potential to be used as diagnostic instruments; they can provide instructors with information about student understanding of key concepts that in turn can be used to guide classroom instruction and improve student learning. Validating the use of these tests as diagnostic instruments requires establishing evidence regarding the concepts and errors assessed by individual items together with techniques for extracting diagnostic information.

In developing CATS, Steif[1] drew upon previous research regarding key concepts and common misconceptions that students demonstrate in reasoning about statics problems. Previous research referred to this assessment as the Statics Concept Inventory (SCI), with a later change of naming convention to the Concept Assessment Tool for Statics (CATS). Both essential conceptual knowledge and common errors have been mapped to individual CATS items based on experts' predictions of student reasoning in different problem situations. From this mapping, the assessment was designed to provide evidence of student misconceptions, or common errors, as well as students' mastery of specific conceptual understanding. Prior multivariate psychometric analysis of inventory and item performance have supported these mappings, including work that proposed a matrix of cognitive attributes applicable to the set of CATS items[2].

This paper describes the results from a verbal protocol study eliciting students' reasoning about key concepts ostensibly required to solve 14 CATS items with the goal of amassing evidence to extend the instructional value of CATS. The research questions guiding this study were:

- How is students' thinking about key concepts and skills in statics represented in verbal descriptions of their reasoning while solving CATS items?

- To what extent does students' thinking align with the presumed set of skills and errors underlying the design and proposed interpretation of CATS items?

Facets of Understanding

This study was guided by related work of Minstrell[3-4] and his colleagues on facets of student understanding, in which diagnostic analysis of students' conceptual understanding can be used by instructors to design more targeted and meaningful instruction. Qualitative research methods, specifically verbal think-aloud protocols, were employed to further validate proposed models of cognitive skills and student errors.

In his work in physics, Minstrell[3] has attempted to understand students' thinking with the goal of designing assessment tools that yield information for improving instruction. He argues that assessment instruments that are scored with a two point rubric (either answered correctly or incorrectly) are not useful in determining student thinking behind incorrect responses because they provide little information about how to help students correct their thinking[4]. The process followed by Minstrell in developing more diagnostic assessment items was to first identify and organize students' thinking into both desired and problematic aspects of thinking — both referred to as facets. The facets describe students' thinking as it was seen or heard in the classroom and represent individual pieces of students' knowledge or strategies of reasoning[3]. These facets were clustered within particular domains of understanding, such as force and motion. For each cluster, facets were organized as: (a) appropriate or acceptable understanding for introductory physics, (b) arising from formal instruction, but either overgeneralized or undergeneralized in application, or (c) more problematic and needing instructional intervention to prevent student difficulty with the cluster or ideas in related clusters[3]. This information was used in turn to develop items in which the answer choices were associated with specific facets of student thinking. In summary, Minstrell recommends the use of qualitative research strategies, such as open-ended interviews, focus groups, or think-alouds, to diagnose students' misconceptions.

Research Design

Participants: The present study was based on interviews from eighteen undergraduate engineering students from a large, public Midwestern university, each of whom had completed a statics course within the prior academic year. The sample consisted of 13 males and 5 females. The students' grades in statics ranged from A+ to C. All of the students were either second- or third-year undergraduate engineering students; the sample included students majoring in mechanical, civil, and industrial engineering.

Instrument: CATS is a twenty-seven question multiple-choice instrument designed to diagnose students' correct and incorrect understandings of statics concepts[1]. The developer of CATS designed three items for each of nine concepts: (a) Drawing forces on separate bodies, (b) Newton's 3rd Law, (c) Static Equivalence, (d) Roller joint, (e) Pin-in-slot joint, (f) Loads at surfaces with negligible friction, (g) Representing loads at connections, (h) Limits on friction force, and (i) Equilibrium. Subsequent research has identified a set of ten cognitive attributes or skills for which mastery is required to select a correct response among distractors[2]. Table 1 presents a list of these skills and their descriptions.

Table 1. Cognitive Attributes (Skills) identified for CATS[1]

Cognitive Attribute	Name	Description
S1	Equivalence	Static equivalence between forces, couples, and combinations.
S2	Newton's 3rd Law	Forces between two contacting bodies must be equal and opposite.
S3	Contact Forces	Direction of force between frictionless bodies in point of contact.
S4	Friction Forces	Implication of equilibrium and Columbus Law of friction force (force must be less than or equal to the coefficient of friction)
S5	Pin on Slot	Representation of pin-on-slot.
S6	Roller Support	Representation of roller support (one force perpendicular to the contact surface).
S7	Fixed Support	Representation of Fixed support (two forces in the x-y direction and a moment).
S8	Representation and Tension in Ropes	Identifying forces acting on the corresponding blocks. Identifying forces on the corresponding ropes. Representation of forces as vectors (Pythagoras Theorem).
S9	Representation of Forces	Identifying forces acting on the corresponding clocks. Representation of pin support.
S10	Couples and Equilibrium	The moment exerted is the same about any point. Consideration of force and moment balance in equilibrium.

Each problem was designed to require qualitative reasoning and could be solved without the need for mathematical computation[1]. The problems were also designed to identify conceptual errors or misconceptions. In developing CATS, Steif drew upon a set of distinct errors that reflect known misconceptions exhibited by students. These were based on his classroom experience and frequent occurrence in student work[5]. Table 2 presents a list of these common errors and their descriptions.

Table 2. Common Errors in Statics[1]

Error	Description
CE1	Failure to be clear as to which body is being considered for equilibrium.
CE2	Failure to take advantage of the options of treating a collection of parts as a single body, dismembering a system into individual parts, or dividing a part into two.
CE3	Leaving a force off the free body diagram (FBD) when it should be acting.
CE4	Drawing a force as acting on the body in the FBD, even though that force is exerted by a part which is also included in the FBD.
CE5	Drawing a force as acting on the body of the FBD, even though that force does not act directly on the body.
CE6	Failing to account for the mutual (equal and opposite) nature of forces between connected bodies that are separated for analysis.
CE7	Ignoring a couple that could act between two bodies or falsely presuming its presence.
CE8	Not allowing for the full range of possible forces between connected bodies, or not sufficiently restricting the possible forces.
CE9	Presuming a friction force is at the slipping limit (μN), even though equilibrium is maintained with a friction force of lesser magnitude.
CE10	Failure to impose balance of forces in all directions and moments about all axes.
CE11	Having a couple contribute to a force summation or improperly accounting for a couple in a moment summation.

Methodology: A sample of eighteen undergraduate engineering students was obtained through email recruitment. The students were required to have completed a statics course within the previous academic year and needed to be able to explain their thinking processes in fluent English when solving a problem. Eligible students were then interviewed and compensated for their participation; each interview was completed within a two-hour window. In the interviews, each student was presented with one of two booklets that contained 8 CATS items each. The selected items were chosen for specific combinations of skills and errors, with a breadth of item difficulty. The items increased in difficulty across each set of 8 with some separation between items that addressed similar concepts. The CATS items selected for this study are described in Appendix A.

The interview protocol was informed by findings from a previous pilot study[6]. As students' reasoning and thinking cannot be determined from response choices alone, researchers prompted students to explain their line of reasoning for individual CATS items and to describe why they did not select alternate responses. Students were encouraged to verbally explain their thinking as they initially approached each problem and after arriving at an answer, students were prompted for further explanation regarding specific aspects of the problem and why they did not select alternate responses. Researchers opted to question students iteratively by returning to previously answered problems after addressing all of the items in the booklet. Further prompts regarding interpretation of problem statement and representations, and specific aspects of student reasoning were posed to students to allow for multiple modes of student explanation. Audio recordings were taken at the time of the interviews and transcripts were created to analyze students' conceptual understandings.

Verbal think-aloud protocols combined with qualitative analysis of students' statements were used to validate experts' predicted student errors and expected cognitive skills for each CATS item. A summary of the skills and common errors identified for each item is presented in Figure 1 below.

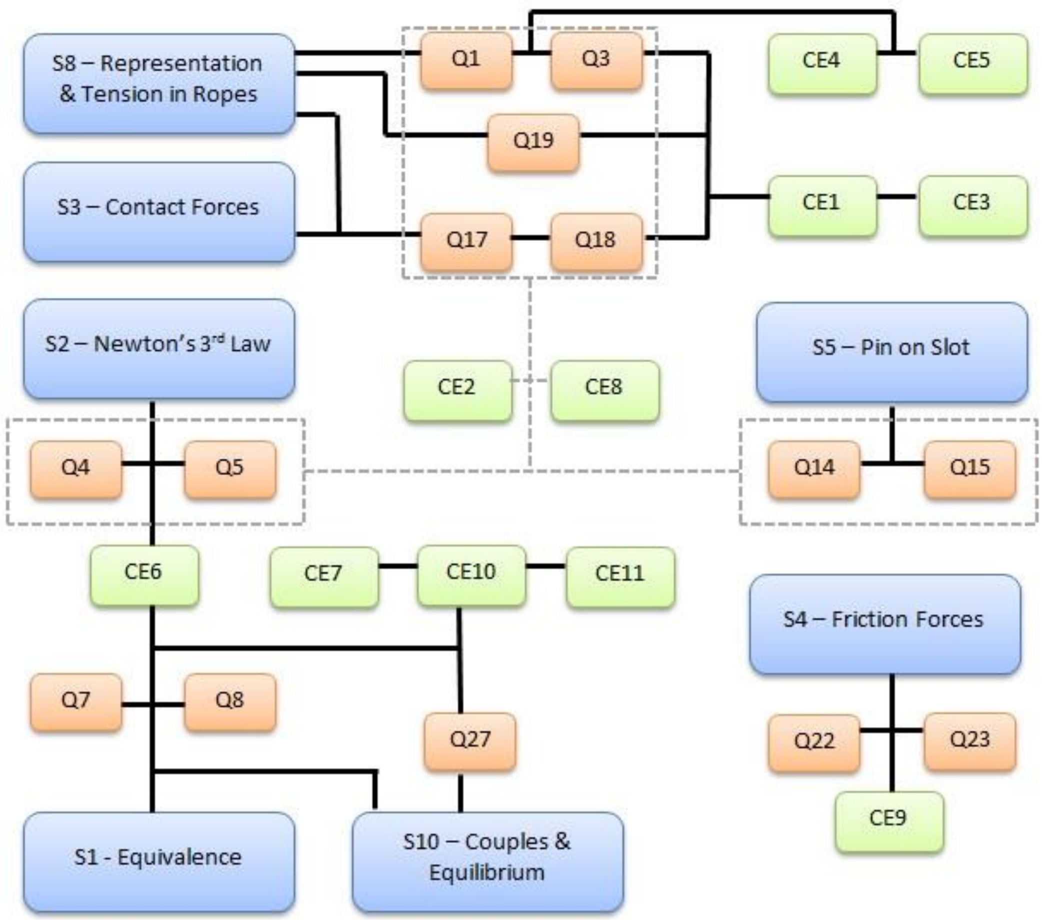

Figure 1. Cognitive attributes (skills) and statics errors identified for each CATS item

As noted above, students were prompted to explain their line of reasoning for selected CATS items and to describe why they did not select alternate responses. The previously identified skills and errors were then used as part of an analytic coding scheme that allowed for the emergence of additional concepts and errors beyond those originally posited for each item. Interview transcripts were analyzed in an iterative manner to identify: (1) utterances in student responses that could indicate concepts used to solve problems, (2) conceptual errors students made and also (3) the presence of the previously identified skills for each of the items selected. A minimum of three passes of the transcripts yielded a stable coding system based on the expected skills and errors. Additional analysis passes focused on emergent themes.

Results

In order to identify student thinking in verbal explanations and response behavior, transcript analysis yielded identification of possible sub-skills as well as indicators of expected skills. Here we use the term indicator to refer to specific lines of thinking found in transcripts that were coded as evidence for particular skills or errors. Table 3 presents a list of indicators for CATS skills.

Table 3: Indicators of Skills in Student Transcripts

Skill	Description	Indicators
S1	Equivalence	• Consideration of both forces and moments when evaluating equivalent systems
S2	Newton's 3rd Law	• "Equal and opposite forces" • Balancing/Counteracting applied force between two contacting parts
S3	Contact Forces	• Acknowledging contact force pair as only interaction between contacting bodies (no moment or couple) • Normal or perpendicular direction of forces at contact point
S4	Friction Forces	• Evaluation of system with friction for static or dynamic state
S5	Pin on Slot	• Identification of joint as pin in slot • Normal or perpendicular direction of forces at contact point • Indicating degrees of freedom: rotation and transverse along slot
S6	Roller Support	• Identification of joint as roller • Normal or perpendicular direction of forces at contact point • Indicating degrees of freedom: transverse along surface
S7	Fixed Support	• Identification of joint as fixed support • Inclusion of x-y forces and moment • Indicates zero degrees of freedom
S8	Representation and Tension in Ropes • recognizes internal forces • recognizes redundant forces	• Correctly defining system and identifying forces within a free body diagram • Correct vector representation of forces acting on evaluated bodies • Excludes forces internal to the system in free body diagram • Excludes forces that do not act directly on defined system in free body diagram
S9	Representation of Forces	• Correct vector representation of forces acting on evaluated bodies • Identification of joint as pin • Inclusion of x-y forces • Indicating degrees of freedom: rotation
S10	Couples and Equilibrium • sum of forces equals zero • sum of moments equals zero	• Evaluation of moment is consistent along rigid body • Evaluation of both force and moment in determining equilibrium solution • Evaluation of force for equilibrium, independent of moment • Evaluation of moment for equilibrium, independent of force

Additionally, transcript analysis yielded indicators of misconceptions or common errors in student thinking. Table 4 presents a list of indicators for CATS common errors that provide descriptions and examples of how students' responses indicated CATS common errors.

Table 4: Indicators of Errors in Student Transcripts

Error	Description	Indicators
CE1	Failure to be clear as to which body is being considered for equilibrium.	• Inclusion of parts external to system in free body diagrams • Reference to parts of mechanism that do not contribute to system being evaluated, as evidence of response o Ex: Rollers in Item 14, Rope in Item 19, Spring in Item 17
CE6	Failure to account for the mutual (equal and opposite) nature of forces between connected bodies that are separated for analysis.	• Allowing for non-opposite forces at joint o Ex: with CE8, literal interpretation of forces in Items 4&5: attempting to find forces at joint that counteract direction of forces shown in diagram
CE7	Ignoring a couple that could act between two bodies or falsely presuming its presence.	• Allowing for a moment to occur at the contact point between two parts
CE8	Not allowing for the full range of possible forces between connected bodies, or not sufficiently restricting the possible forces.	• Constraining a force to one direction instead of allowing for any possible summation of vector components • Allowing for a force to act in a direction that is not possible o Ex: non-normal contact force or support force
CE11	Having a couple contribute to a force summation or improperly accounting for a couple in a moment summation.	• Accounting for a moment in a force summation • Incorrect moment summation

Note: Common errors not included in this table were directly present in student responses, and did not require identification of indicators in student explanations.

Using the CATS skills and errors indicators, researchers were able to identify student utterances and code them using the analytic coding scheme. Transcripts were coded for the expected skills, errors, and indicators along with some description of how the utterance identified could provide evidence of student thinking. This produced quantitative data that could be used to confirm the expected skills and errors for each CATS item. Tallies were created that tracked the number of student responses that provided evidence of skills or errors for each item. This was created for three groups of responses: (1) all student responses, (2) only correct responses, and (3) only incorrect responses. The tallies were then evaluated for strength of confirmation. Evidence of confirmation of thinking based on particular skills in a given item was defined to be strong if it was observed in more than 2/3 of correct student responses; moderate if it was observed in 1/3 to 2/3 of correct student responses, and weak if observed in less than 1/3 of correct responses. Additional skills were only included if there was 2/3 or greater presence in student explanations. Table 5 presents a summary of the CATS skills confirmation results.

Table 5: Confirmation of CATS Skills

Item	Expected Skills	Confirmed/Additional Skills
Q1: Forces on collection of bodies	S8: Representation & Tension in Ropes	S8: Representation & Tension in Ropes
Q3: Forces on collection of bodies	S8: Representation & Tension in Ropes	S8: Representation & Tension in Ropes
Q4: Newton's 3rd Law	S2: Newton's 3rd Law	S2: Newton's 3rd Law *S9: Representation of Forces (Pin Support)*
Q5: Newton's 3rd Law	S2: Newton's 3rd Law	S2: Newton's 3rd Law S9: Representation of Forces (Pin Support)
Q7: Static Equivalence	S1: Equivalence S10: Couples and Equilibrium	*S1: Equivalence* S10: Couples and Equilibrium
Q8: Static Equivalence	S1: Equivalence S10: Couples and Equilibrium	*S1: Equivalence* *S10: Couples and Equilibrium*
Q14: Pin in Slot	S5: Pin in Slot	S5: Pin in Slot
Q15: Pin in Slot	S5: Pin in Slot	S5: Pin in Slot
Q17: Negligible Friction	S3: Contact Forces S8: Representation & Tension in Ropes	S3: Contact Forces
Q18: Negligible Friction	S3: Contact Forces S8: Representation & Tension in Ropes	S8: Representation & Tension in Ropes
Q19: Representation	S8: Representation & Tension in Ropes	S8: Representation & Tension in Ropes
Q22: Friction	S4: Friction Force	*S4: Friction Force* S2: Newton's 3rd Law
Q23: Friction	S4: Friction Force	S2: Newton's 3rd Law
Q27: Equilibrium	S10: Couples and Equilibrium	*S10: Couples and Equilibrium*

Note: Confirmation required strong evidence of skill (presence in greater than 2/3 of correct student responses); italicized skills indicate moderate evidence of skill in student explanations (1/3-2/3 of all student responses).

While the number of student responses for each skill was sufficient for providing evidence of confirmation of skills by item, the number of student responses for each error was insufficient to approach confirmation of errors by item. Since there were few incorrect responses for some items, an error-based approach as opposed to an item-based approach was taken in order to provide evidence of confirmation. For each error, a tally was made of the total number of instances of that error in all student responses. This number was set as a ratio against the total number of possible instances of that error in student responses, or the total number of times that item was answered by all students. Strong evidence of confirmation was found with a ratio greater than 2/3, moderate and weak evidence of confirmation was found with ratios between 1/3-2/3 and less than 1/3, respectively. Table 6 presents a summary of the error-based approach confirmation results.

Table 6: Confirmation of CATS Errors

Common Error	Corresponding Items	Confirmation
CE1: Failure to clarify body in equilibrium	Q-1,3,17,18,19	Moderate
CE2: Failure to treat parts as single system	Q-1,3,4,5,14,15, 17,18,19	Weak
CE3: Leaving force off FBD	Q-1,3,14,15,17,18,19	No Evidence
CE4: Including internal force in FBD	Q-1,3	Strong
CE5: Including non-acting force in FBD	Q-1,3	Strong
CE6: Failure to account for force pair between separated bodies	Q-4,5,7,8	Moderate
CE7: Couple between bodies	Q-7,8,27	No Evidence
CE8: Forces between bodies	Q-1,3,4,5,14,15, 17,18,19	Strong
CE9: Friction force at max	Q-22,23	Strong
CE10: Failure to balance all forces and moments	Q-7,8,27	Strong
CE11: Improper force or moment summation	Q-7,8,27	Moderate

Note: Strength of confirmation determined by ratio of total instances of error in incorrect student responses to total potential expected occasions of error for corresponding items. Strong confirmation was indicated by a ratio larger than 2/3, moderate confirmation indicated by ratio of 1/3-2/3.

Discussion

This study sought to better understand whether student thinking, as observed in students' verbal explanations of their reasoning while solving statics problems, aligns with a set of specific skills and concepts that the problems are designed to tap. The indicators provided in Table 3 illustrate the types of evidence that students may provide in verbal explanations that can demonstrate skill mastery. Interestingly, students tend to display both conceptual and procedural types of thinking. For example, when creating a free-body diagram, students provided evidence of thinking that included the procedural steps in defining a system and determining which forces to include in their diagram. Students also provided explanation of the conceptual underpinning of the procedure, by explaining how internal forces would cancel out and would not be considered external to the system. Future research into the problem-solving strategies taken by students as they solve conceptual problems may provide more insight into relationships between conceptual and procedural understanding.

The second research question guiding this study was focused on the confirmation of the expected skills and errors for each CATS items as previously determined through extensive psychometric analysis. The qualitative data collected and reported as part of this study is intended to serve as additional evidence in a larger validity study and as such is most concerned with providing evidence of confirmation. As seen in Table 5, the majority of skills expected for each CATS item studied are supported with strong evidence of confirmation from student thinking. However, there are a number of items that did not behave as expected. Items Q4 and Q5 which deal with *Newton's 3rd Law* show evidence of confirmation for the associated *Newton's 3rd Law* skill, however there is also evidence that suggests an additional skill, *Representation of Forces*, may be associated with these items. Also, items Q17 and Q18 dealing with systems with *Negligible Friction* were expected to align with skills S3 and S8, *Contact Forces* and

Representation & Tension in Ropes, respectively. While this association was found in item Q17 & skill S3, and item Q18 & skill S8, additional evidence may be needed to support both skills expected to be associated with those items. Finally, strong evidence of confirmation was not found for the expected skill S4 for items Q22 and Q23, dealing with systems with *Friction*. Instead, evidence was collected that suggest an additional skill, *Newton's 3rd Law*, may have some interaction with these items. However, it should be noted that there were very few correct responses to items Q22 and Q23 upon which confirmation could be established. The prevalence of correct responses should be a consideration, for when fewer than half of subjects are getting an item correct, should we expect to find evidence of confirmation for the expected skills?

The matter of how to determine a threshold number of responses to use for deciding when an error was confirmed was an additional concern. Overall, there were very few incorrect responses. This led to the need for an error-based approach across all items for error confirmation, rather than an item-based approach. While some evidence was collected and is presented in Table 6, the evidence can only support that some of the expected errors are present in student thinking. Further research may provide evidence of confirmation for the expected errors associated with each CATS item.

In addition to the data found through the a priori coding scheme, emergent themes were identified and collected through the analysis of student transcripts. One of the themes indicated an additional skill may be present in how students think about the statics problems presented to them. This skill may be considered a separate "understanding of moment", which was seen through indicators of:

- Statement that no moment may exist about a point/pin joint, when free to rotate
- Evaluation of moment is consistent along a rigid body
- Identifies a couple as source of a moment, independent of location along a rigid body

Conversely, evidence was found that suggests additional errors may be due to misconceptions about moments:

- Allowing for the presence of a moment at a point, or about a pin joint
- Failure to recognize that the location of a moment is irrelevant, that the moment about any point on a rigid body is equivalent.

This evidence supports previous findings related to possible common error additions[6], and may suggest that if not an additional skill or error, a fundamental understanding of the nature of moments and couples may be necessary for mastery of the specific skills associated with CATS items.

Transcript analysis of student interviews provided evidence supporting the use of CATS to determine if students have attained mastery of specific cognitive skills and as predictive of student's conceptual mastery. However, evidence reveals limitations of the instruments for diagnosing student errors. For example, student interviews with CATS items have led to the emergence of additional common errors and alternate conceptions of student reasoning not captured in the original assessment design. Based on student responses, it appears that the expert-generated model of knowledge and skills may be sufficient overall, although individual skills may align with specific CATS items differently than expected.

Conclusion

The findings of this study promise several broader impacts. First, they provide evidence of student thinking as a means of validating the diagnostic capability of CATS. Second, the information may enhance the interpretation of student performance on CATS. Third, some of the findings may indicate aspects of CATS that may be considered for modification, including instances of CATS items, multiple choice options, concept descriptions and mappings, and common student error descriptions and mapping. Finally, an identification of trends in how students conceptualize statics problems may prove useful to inform statics instruction in general.

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Appendix A: Description of CATS Items Discussed in this Paper

Sample items and the full version of CATS for instructional purposes may be found on ciHUB.org.

Q1: Given a system of blocks held by ropes, determine the correct free body diagram.

Q3: Given a system of blocks held by ropes, determine the correct free body diagram.

Q4: Given a frame subjected to a variety of forces, determine the correct representation of forces acting at a separated pin joint.

Q5: Given a frame subjected to a variety of forces, determine the correct representation of forces acting at a separated pin joint.

Q7: Given a solid body held at equilibrium with a couple, determine a correct representation of an equivalent system.

Q8: Given a solid body held at equilibrium with a force, determine a correct representation of an equivalent system.

Q14: Given a mechanism with a force applied at a distance from a pin on slot joint, determine the correct direction of force exerted by the slot on the pin.

Q15: Given a mechanism with a force applied at a distance from a pin on slot joint, determine the correct direction of force exerted by the slot on the pin.

Q17: Given a mechanism with a curved body in contact with another curved member, determine the direction of force at the contact point.

Q18: Given an arm connected to a surface by a pin joint, determine the possibility of reaction force scenarios at the pin.

Q19: Given a plate connected to a surface by a pin joint and rope, determine correct representation of reaction forces at the pin.

Q22: Given three stacked blocks with a variety of lateral forces, determine the horizontal component of a force on a surface of one block.

Q23: Given two stacked blocks with a later force on the bottom block, determine the horizontal component of the force exerted by the floor on the lower block.

Q27: Given an L-shaped member that is free to move with forces acting at different locations, determine the correct representation of an additional load that would lead to equilibrium.