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Student Metacognitive Reflection on a Conceptual Statics Question

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Abstract

Many engineering problems assigned in undergraduate classes are numerical and can be solved using equations and algorithms—for example, truss problems in statics are often solved using the method of joints or the method of sections. Concept questions, which can be administered in class using active learning pedagogies, aid in the development of conceptual understanding as opposed to the procedural skill often emphasized in numerical problems. We administered a concept question about a truss to 241 statics students at six diverse institutions and find no statistically significant differences in answer correctness or confidence between institutions. Across institutions, students report that they are not accustomed to such non-numerical concept questions, but they grapple in different ways with the experience. Some frame engineering as inherently numerical, and thus do not value the conceptual understanding assessed by the question, while others recognize that developing conceptual knowledge is useful and will translate to their future engineering work.

Introduction

Both *conceptual knowledge* and *procedural skill* are important aspects of engineering work and in teaching engineering. According to Rittle-Johnson et al. [1], conceptual knowledge is defined as "understanding of the principles that govern a domain," while procedural skill is "the ability to execute action sequences to solve problems." This distinction is commonly discussed in mathematics education [1, 2, 3, 4] but also in other fields, including biology [5], chemistry [6], engineering design [7], electrical engineering [8], structural engineering [9], and statics [10]. In this work, we investigate conceptual understanding in statics, a core course in undergraduate mechanical and civil engineering education that is also often taken by students in other engineering majors. Engineering problems presented to college students typically have a single, numerical correct answer which can be obtained by following an algorithmic problem-solving technique [11]. Such problems often foreground procedural skill above conceptual knowledge. This prioritization may leave students able to solve specific types of problems through pattern matching to their algorithms, but unable to use conceptual understanding to translate their knowledge to new situations [12].

One way that researchers have attempted to develop and assess conceptual knowledge is by using concept questions, often administered in class using the active learning pedagogy of peer instruction, in which students answer a concept question, discuss it in small groups, and then answer it again [13]. These questions have been shown to promote conceptual understanding through pre- and post-tests, often using concept inventories [13, 14, 15].

It is important to understand how students make sense of the role concept questions play in their learning. Researchers have investigated the development of student reasoning by analyzing written explanations of responses to these questions [16, 17, 18], student input has been used to validate questions [19, 20, 21], and student perceptions of problem-solving in engineering have been investigated [22]. This previous work sheds light on student thinking, but in this study, we are specifically interested in metacognition, i.e., students' thinking about their thinking [23, 24].

Previous studies on student metacognition of concept questions have focused on their self-reported confidence in their answers to specific questions [16, 25]. In this work, we extend the investigation about student metacognition of concept questions, by investigating how a concept question fits into students' ideas about what learning statics means. Given the prevalence of procedure-focused, numerical problems in undergraduate engineering education [11], we investigate students' framing of engineering by asking them whether a concept question made them think deeply about the course material. Their responses grant insight into their metacognition as they process the relationship between this question and their broader experiences with statics education.

Background

Procedural Skill and Conceptual Knowledge

Disciplinary knowledge is commonly thought of as existing on three levels, but how those levels are defined varies by field. For example, chemistry knowledge has been described as including macro (visible phenomena), sub-micro (atomic interactions), and symbolic (written chemical reactions) levels, while physics knowledge includes macro, invisible (forces), and symbolic (mathematical equations) levels, and biology knowledge includes macro, micro (cells), and biochemical (DNA, etc.) levels [26].

Similarly, we propose three levels for the statics context: the macro (a truss bridge spanning a river), the conceptual (forces acting on a given member within the truss), and the symbolic (the equilibrium equations relating the forces). While the macro level is tangible, the conceptual and symbolic levels are not directly visible and are a focus of engineering teaching.

Conceptual knowledge is related to understanding conceptual level. Rittle-Johnson et al. define conceptual knowledge as "implicit or explicit understanding of the principles that govern a domain and of the interrelations between units of knowledge in a domain." It is "flexible and not tied to specific problem types and is therefore generalizable" [1]. Procedural skill, "action sequences for solving problems" [27], works at the symbolic level, providing students with algorithms and strategies for solving specific types of problems. Procedural skill allows students to correctly solve problems without necessarily understanding the link between their methods and the underlying concepts, or between the symbolic and conceptual levels of knowledge, thus limiting their ability to apply their knowledge to new types of problems [28].

Concept Questions

Concept questions are multiple-choice questions that are answered without numerical calculations, and thus require conceptual knowledge instead of procedural skill. In this work, concept questions are delivered via the Concept Warehouse [29], an online tool that contains concept questions on a variety of subjects and facilitates the administration of those questions to students. Instructors may interact with the tool in a variety of ways. For example, they can add their own questions to the database, or use existing concept questions; or administer questions through the tool or they can download questions and administer them on paper or via another system; in administering questions using the tool, they can assign the questions as homework, or use them as an element of active learning in class.

One example of a way of using active learning in the classroom with the Concept Warehouse is through peer instruction [30]. In peer instruction, students answer the concept question, discuss it in pairs or small groups, and re-answer the question after their discussion. This practice can be modified by collecting student explanations of their answer in addition to their multiple-choice selection, which is also facilitated by the Concept Warehouse. The use of concept questions, and specifically peer instruction, has been shown to enhance student learning [31, 32]. In this work, we extend the research to investigate student epistemological frames regarding concept questions.

Theoretical Framework

We adopt the conception of personal epistemologies put forth by Elby and Hammer [33, 34], in which epistemological *resources* are combined into *frames*. Resources are “fine-grained knowledge elements,” often subconscious, which can be taught or can arise from lived experience; an epistemological resource might be an idea that knowledge can be memorized. Different resources are activated in different situations—a memorization resource might be less likely to be activated in an art class than an idea that knowledge can be created.

Resources are interconnected, and the activation of one resource may promote or inhibit the activation of others. When a network of resources is activated and stabilized, it can form a frame [35]. This stabilization can occur due to the context (for example, the types of assignments given in a course) or deliberate choice and may become structurally stable with sufficient reinforcement. Two people, or the same person in two different contexts, may have access to the same resources, but assemble the resources into very different frames, leading them to approach a question in different ways.

Research Question

Overall, our research question is: How do student responses—including not only their multiple-choice selection but also their explanation and response to follow-up questions—to a conceptual statics question compare across diverse institutional contexts? To address this overall question, we ask more specifically:

a. How are student correctness, confidence, and their metacognitive reflections on the question related to their institution?
b. What do the student responses suggest about their epistemological frames in learning statics?

Methods

Question Administration

For this study, we selected one concept question which was administered via the Concept Warehouse [29] (ConcepTest #4606), as shown in Figure 1. The question was delivered to 241 students at six institutions. All students consented to participating in the research study. Figure 1 shows the question as it appears to students. The correct answer is the third choice: AD and BD are in compression, while AC, BC, and CD are in tension.

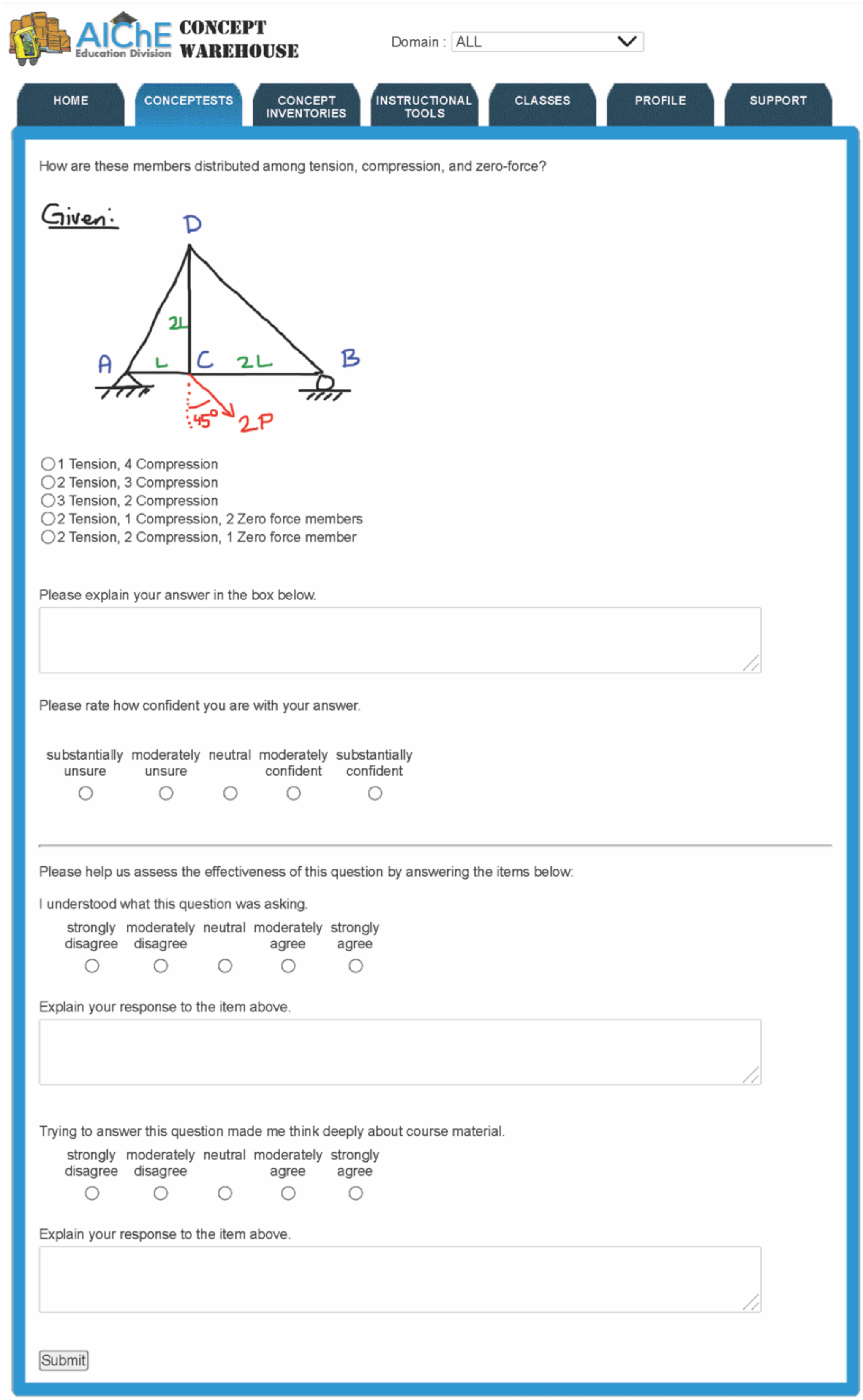

Figure 1. Student view of the concept warehouse question used in this study.

Table 1 shows the pseudonyms we assigned each of the six institutions, summarizes their key characteristics, and gives the number of students at each institution who answered ConcepTest #4606. All students from a given institution studied here were in the same course, and therefore were administered the question in the same instructional setting, but students at different institutions may have answered the question in different modalities. For example, for some, the question might have been part of a homework assignment, while for others it may have been used during lecture to stimulate active learning. Similarly, only a subset of instructors included follow-up questions asking students to explain their answer and answer whether they understood what the question was asking and whether it made them think deeply about the course material, as shown in Figure 1. We selected only cases where all of those follow-ups were part of the assignment and where the students provided consent to participated in the study. This study was conducted as part of a larger project to facilitate and study the use and propagation of the Concept Warehouse in mechanical engineering. [36]

Table 1. Institutions

Institution Pseudonym	Characteristics	Number of Students
University A	Large, teaching-focused, public	104
University B	Large, research-focused, public	68
University C	Small, teaching-focused, private	26
University D	Medium, teaching-focused, public, minority-serving institution	23
University E	Medium, teaching-focused, public community college	11
University F	Medium, teaching-focused, public	9
total		241

Statistical Analysis

Pairwise analysis (for example, to compare students' reported confidence in their answers at two institutions, or between students who selected correct and incorrect answers) was performed using two-tailed Mann-Whitney tests with corrections for ties and continuity. To analyze multiple groups (for example, to learn the relationship between correctness and institution overall), Kruskal-Wallis tests were used. In all cases, 95% confidence was used to determine statistical significance. Both test types were chosen to account for our non-parametric data and to avoid assuming normality.

Qualitative Analysis

Student responses were coded by the first author using Atlas.ti and discussed with the second author until consensus was reached. Initial code categories for the long-form response questions were developed based on the questions, and emergent coding was used to develop specific codes. Question clarity codes include "unambiguously clear," "clear but difficult," "eventually clear," and "could be clearer." Codes pertaining to the question about thinking deeply were divided into groups based on the participant's impression about the conceptual nature of the question: codes include "no numbers difficult," "no numbers unimportant," "no numbers different," "no numbers conceptual," and "no numbers good." Student responses are reproduced here exactly as they were submitted; grammar and spelling errors were not corrected.

Question Validation

To validate the question quality, we examined student responses to the statement "I understood what this question was asking," and the results are summarized in Table 2. The average response on this question was 4.52 out of 5, with 5 corresponding to "strongly agree," and there was no statistically significant difference between students who answered the question correctly and incorrectly either overall ($p = 0.59$) or at any institution ($p > .05$). We use this item to determine whether the concept question was clear to students, and at all institutions, the answer appears to be "yes." However, there were small pairwise differences in understanding the question among institutions: A-B ($p = .004$); A-D ($p = .005$); and C-D ($p = .03$), and a Kruskal-Wallis test indicated a statistically significant difference overall between understanding the question and institution ($p = .01$).

Table 2. Understanding the question

	number of responses	understanding the question		
		incorrect	correct	total
overall	241	4.47	4.58	4.52
University A	104	4.51	4.80	4.65
University B	68	4.48	4.18	4.35
University C	26	4.65	4.78	4.69
University D	23	4.07	4.33	4.17
University E	11	4.38	4.33	4.36
University F	9	4.75	4.80	4.78

In their explanations of their response, most (152) students submitted answers we coded as "unambiguously clear." For example, one student from University C wrote, "The question was very understandable and straightforward." Many (19) felt that the question was clear but added that it was difficult for them. For example, one student from University F wrote, "I understand the question but have a hard time coming to a conclusion step by step," and another from University D said, "This question was simple the answer not so much." We conclude that the students understood what the question was asking, whether they got it right or wrong, and that therefore students who answered the question incorrectly did so due to some difficulty with the material, not due to the question wording.

Results

In this section we report student answers to the concept question and follow-ups shown in Figure 1, beginning with a statistical analysis of the multiple-choice items. Overall and for each institution, we summarize the results in Table 3. The fraction of students who answered correctly is given, and for the Likert-scaled items ("Please rate how confident you are with your answer," where 5 is "substantially confident," and their agreement with the statement "Trying to answer this question made me think deeply about course material," where 5 is "strongly agree"), the average student answer is given, and the responses are also dis-aggregated by answer correctness. We first compare answer correctness across institution, then analyze the relationship between both Likert-scaled items and both answer correctness and institution.

Table 3. Statistical Data

	number of responses	fraction correct	answer confidence			perception of deep thinking		
			incorrect	correct	total	incorrect	correct	total
overall	241	0.44	3.33	3.66	3.47	4.21	4.21	4.21
University A	104	0.49	3.32	3.88	3.60	4.34	4.27	4.31
University B	68	0.41	3.35	3.32	3.34	3.88	3.75	3.82
University C	26	0.35	3.35	3.33	3.35	4.24	4.44	4.31
University D	23	0.39	3.14	3.89	3.43	4.79	4.56	4.70
University E	11	0.27	3.38	4.00	3.55	4.50	4.67	4.55
University F	9	0.56	3.75	3.20	3.44	3.00	4.80	4.00

In summary, we find that across the institutions given in Table 1, students performed similarly in terms of correctness. Students who answered correctly were more confident than those who answered incorrectly, and there was no relationship between students' confidence and their institution. When asked whether the question made them think deeply about the course material, responses differed significantly by institution, but did not depend on answer correctness. We therefore argue that institutions, or instructors, that prepare students similarly in the skills required to answer a question may instill very different attitudes about learning, i.e., different student epistemological frames.

Answer Correctness

This question was challenging, with 44% of the 241 students selecting the correct answer. The fraction correct ranged from 27% to 56% between institutions. The instructors at each institution used the tool in different ways depending on their contexts, so differences in student performance cannot be attributed solely to institutional factors—for example, some students may have been given this question during their first lesson on trusses, while others may have been assigned it during final exam review. We found that correctness does not statistically-significantly depend on institution ($p = .53$). In addition, student correctness at each institution was compared pairwise to each other institution and none of the differences in correctness rate were found to be statistically significant ($p > .14$ in all cases), showing that the institutions in this study prepared their students approximately equally well to answer this question correctly.

Confidence

Overall, students who selected the correct answer were more confident in their choice (3.66 *vs* 3.33, $p = .008$). However, only University A, the institution with the most participants, had a difference that was statistically significant (3.88 *vs* 3.32, $p = .002$). There was no statistically significant relationship between confidence and institution overall ($p = .54$) or between any pair of institutions ($p > .08$ in all cases).

Thinking Deeply

Students generally agreed that the question made them think deeply about the course material (4.21), with no difference between students who answered correctly and incorrectly ($p = .95$). There was also no statistically significant difference between students who answered correctly and incorrectly at any institution ($p > .05$).

However, there are statistically significant cross-institutional differences in whether students felt that the question made them think deeply about the course material. The overall Kruskal-Wallis *p*-value is .00006, and the institution pairs with statistically significant differences are: A-B ($p < .001$); A-D ($p = .005$); B-C ($p = .02$); B-D ($p < .001$); B-E ($p = .01$); and C-D ($p = .03$). Despite the lack of cross-institutional significant differences in correctness and confidence, and of differences in response to the thinking deeply question from students who got the question right and wrong within an institution, there are significant cross-institutional differences in the thinking deeply score. Students' self-assessment of their deep thinking appears to depend on their institutional learning context, even among institutions equally likely to have their students answer correctly. To learn more about student thinking in response to this concept question, we turn to a qualitative analysis of their written explanations in response to the deep thinking prompt.

Written Responses

In explaining their response to the statement "Trying to answer this question made me think deeply about course material," across institutions, students made it clear that they are not accustomed to questions without numbers, which cannot be solved using numerical equations. One student from University A said, "I thought about it more conceptually. I usually rely on math to determine compression and tension, but just using logic and the basic concepts, I think I was able to correctly solve this without a lot of math" (they did select the correct answer). However, students grappled in diverse ways with being confronted with this type of problem, which are reflected in their conceptions of their own "deep thinking."

Some students convey a belief that thinking deeply in engineering requires numerical answers, and therefore that this question did not make them think deeply. One student from University A (thinking deeply = 4) said, "I only had to think about the conceptual side of two-force members, I don't think I had to think too deeply because I wasn't solving for reaction forces or forces in the members," and another from University B (thinking deeply = 3) said, "there is no math involved so it's not really asking vital material."

Others related the difficulty of the problem to the extent to which it made them think deeply. One student from University B (thinking deeply = 3) said, "You didn't have to think super deep about it, you just had to look at it for a second," implying that the question was easy and therefore did not require deep thinking—they did, however, select an incorrect answer. On the other hand, many students said that the lack of numbers made the question more difficult for them, which required them to think more deeply. One student from University A (thinking deeply = 5) said, "As I was not able to numerically solve the problem, I had to think hard about how to conceptually find the answer. It made me think about the most strategic junction to start at and also made me think about the bridge as a whole to check to see if my thoughts were logical," and another (thinking deeply = 5) said, "I am not confident with working through conceptual problems in my head without using numbers, so this problem forced me to break apart the body and consider how internal and external forces would interact." One from University B (thinking deeply = 3) said, "The question itself is not that deep, but trying to answer without working anything out did require some extra thought." Another from University F said, "I had to think very hard and draw free body diagrams in order to understand and visualize the direction of the forces in the members. I think it would be easier if there were some magnitudes and dimensions added so that the forces could be calculated and make it easier to determine the forces in the members.”

Students who objected to the lack of numbers in the problem, feeling that the addition of numbers would make them think more deeply, felt that the lack of numbers made the problem ambiguous. One student from University B (thinking deeply = 2) said, “I don't think this was that helpful. I think students get a better understanding by working out the numbers rather than having to make assumptions based off a drawn diagram,” and another from University A (thinking deeply = 4) said, “It's a little vague when its all conceptual with variables and no values for the forces or lengths.” These responses contrast with the reasoning given by students who expressed that the lack of numbers made them think more deeply. One student from University A (thinking deeply = 4) said “Normally I am given a problem with numbers and I just plug and chug. However, I feel like this problem allowed me to think about the relationships between the members more conceptually to figure out the sign.” A classmate (thinking deeply = 5) said, “Conceptual questions with no numbers really help me understand the basic concept behind the material making it easier when numbers are involved.” A student from University B (thinking deeply = 5) said “I had to be able to think deeper about the meaning behind the concepts rather than just using numbers to calculate a value,” and a classmate (thinking deeply = 5) said “i had to think about the defintion of what the whole concept of our learning versus just doing the math.” The students who feel that this question made them think deeply about the course material believe that working through non-numerical questions forces them to understand the underlying concepts, which requires deeper thinking than “just” using equations to reach a numerical answer.

Discussion

The question studied was challenging, with less than half the students able to select the correct answer. Across institutions, there was no statistically significant difference in the fraction of students who answered the question correctly or their reported confidence in their answers, indicating that the students have similar levels of conceptual understanding needed to answer this question. However, students’ degree of agreement with the statement “trying to answer this question made me think deeply about the course material” depended strongly on their institution (p = .00006). We conclude that even if students demonstrate similar understanding to answer a question correctly, their metacognitive reflection on the question, which sheds light on their epistemological frame, can differ significantly.

Many students struggled with the conceptual nature of the question, preferring to rely on procedural skill (“After assigning the values of P=2, and L=2, I solved for…”). These responses align with a framing of engineering as fundamentally numerical (“there is no math involved so it's not really asking vital material”), with answers reached via algorithmic techniques. Others, however, acknowledge that they are accustomed to numerical problems (“Normally I am given a problem with numbers and I just plug and chug”)—i.e., their engineering assignments have been numerical and algorithmic—but they exhibit a different framing; they value “understand[ing] the basic concept behind the material,” which they can then apply “when numbers are involved.”

In assessing student learning, educators commonly look first for correctness: were students able to demonstrate a certain set of skills needed to answer a question? In distinguishing procedural skill from conceptual knowledge, researchers might also assess conceptual understanding: do students know how to plug numbers into problem-solving algorithms, or do they also understand the underlying concepts? Concept questions like the one used in this study can be used to make this distinction, since they cannot be directly solved using numerical algorithms. We now advocate for a third consideration: how are students making sense of their formation as engineers? The results of this study indicate that even students who have comparable procedural skill and conceptual knowledge—i.e., the students at the six institutions studied here, which showed no statistically significant difference in answer correctness—may still have different epistemological framings of what it means to be an engineer. However, this conclusion is based on limited data and more research is needed to verify the extent of this finding.

In future work, we will further examine students' epistemologies by analyzing their explanations of their multiple-choice selection and by expanding the sample size of students. We will also interview statics instructors to characterize instructor epistemologies and on classroom and institutional factors that may influence students' epistemological framing of engineering.

Conclusions

Students from six different institutions, ranging from a community college to a large research-intensive university to a minority-serving institution, were asked to answer a concept question involving compression and tension in a truss. In addition to their answer selection, students were asked to explain their choice, rate their confidence in their answer, rate their agreement with statements that they understood what the question was asking and that the question made them think deeply about the course material, and to explain their responses to the last two statements. Out of 241 students, 44% selected the correct answer, and despite the differences in institutional context, there were no statistically significant differences in answer correctness or student confidence between institutions.

However, even though students at each institution did not differ significantly in their likelihood of answering the question correctly, there were significant differences in whether students felt that the concept question made them think deeply about the course material. We conclude that groups of students with similar levels of conceptual understanding may differ in another dimension of learning: their epistemological framing of engineering problems. Some students frame engineering as fundamentally numerical, and thus report that this problem is not "vital material," while others value conceptual understanding as necessary, or at least helpful, in solving engineering problems.

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