

## **Examining engineering concepts in practice: Is conceptual understanding relevant to practice?**

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# Examining Engineering Concepts in Practice: Is Conceptual Understanding Relevant to Practice?

## Introduction:

Traditional means of engineering education focuses on transmitting conceptual knowledge to students so that they can apply such knowledge to unique situations that they will encounter in the engineering workplace. Therefore, it is important to understand how students and practicing engineers are similar and different in their knowledge and application of specific concepts.<sup>1</sup> The research presented in this paper highlights several research activities and findings pertaining to conceptual understanding, reasoning, and application amongst students and practicing engineers. Results from these activities indicate that fundamental conceptual knowledge without engineering context-based application can lead to oversimplification and inaccurate applications of concepts. Implications and suggestions for engineering education based on these findings are then presented at the end of this paper.

## Activities and Findings:

### *Activity 1: Concept Inventory Responses from Practicing Civil Engineers*

We collected responses from about 100 practicing civil engineers for each of the three concept inventories: statics, strength of materials, and fluid mechanics.

### *Findings*

We compared the overall scores and the response patterns on each concept inventory question between students and practicing engineers on the statics, strength of materials (SoM), and fluid mechanics (FM) concept inventories. For the statics concept inventory results, the average student score is 47.6%. The average years' of experience for engineers is 11 and the average score is 40.5%. Students performed better at a statistically significant level on 13 of the 27 questions. There was no statistically significant difference in performance on the remaining 14 questions. The average score for structural engineers is 55.1% and for non-structural engineers is 33.5%.<sup>2</sup> The following two examples show the patterns of misconceptions in students and engineers.

For the strength of materials concept inventory results, the average student score is 43.3%. The average years of experience for engineers is 11 and the average score is 50.9%. Engineers performed better at a statistically significant level on 7 of the 23 questions. Students performed better than engineers at a statistically significant level on 3 of the 23 questions. The average score for structural engineers is 56.0% and for non-structural engineers is 47.6%.<sup>3</sup> The following two examples show the patterns of misconceptions in students and engineers.

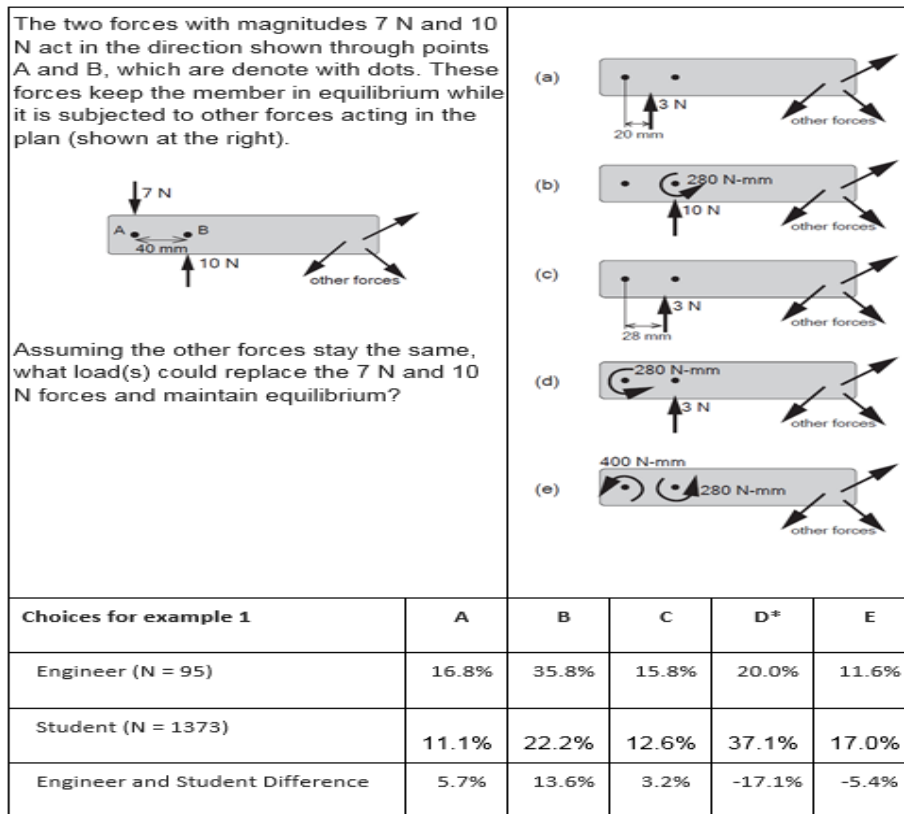


Figure 1: Statics Concept Inventory Example 1

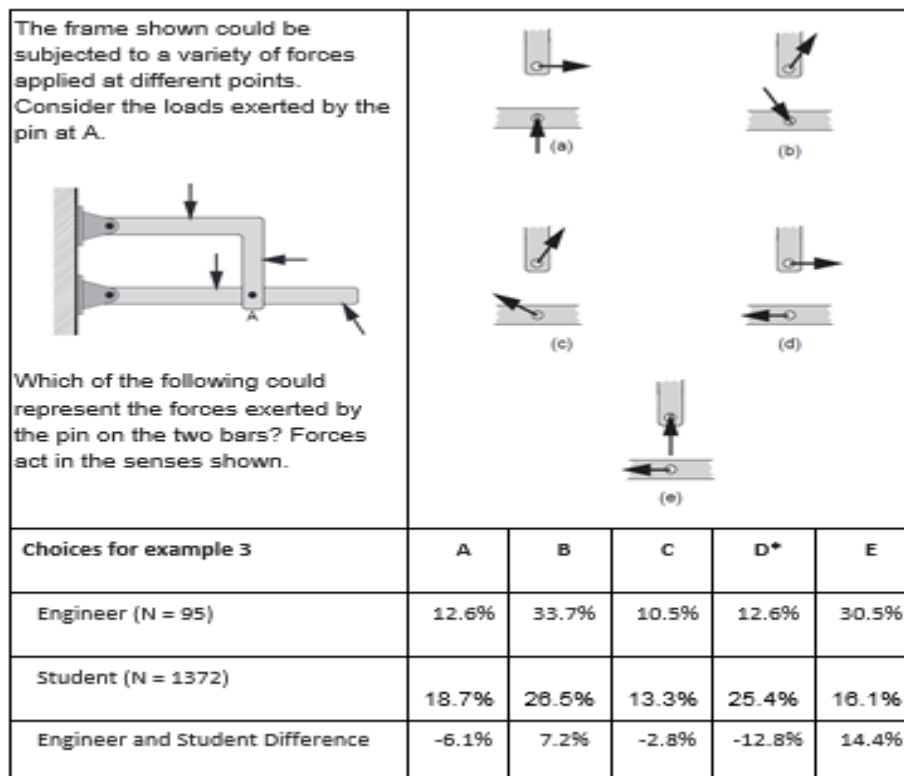
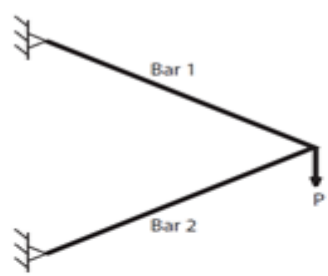


Figure 2: Statics Concept Inventory Example 3

5. Which of the two identical slender steel bars will fail first in the structure below as the load (P) gradually increases?




a) Bar 1  
b) Bar 2  
c) Both bars will fail at the same time

Choices for Q5	A	B	C
Engineer (N = 109)	16.5%	57.8%	25.7%
Non-STR Engineer (N = 66)	24.2%	42.4%	33.3%
STR Engineer (N = 43)	4.7%	81.4%	14.0%
Student (N = 137)	19.0%	33.6%	47.4%
Engineer and Student Difference	-2.5%	24.2%	-21.8%

Figure 3: SoM Concept Inventory Question 5

20. The cylinder at right is made of a ductile material such as steel. The cylinder will fail in (circle one answer):

a) tension  
b) compression  
c) shear  
d) none of the above



Choices for Q20	A	B	C	D
Engineer (N = 109)	81.7%	5.5%	10.1%	2.8%
Non-STR Engineer (N = 66)	77.3%	6.1%	12.1%	32.3%
STR Engineer (N = 43)	88.4%	4.7%	7.0%	0.0%
Student (N = 137)	50.4%	5.1%	36.5%	8.0%
Engineer and Student Difference	31.3%	0.4%	-26.4%	-5.3%

Figure 4: SoM Concept Inventory Question 20

The average student score for the fluid Mechanics concept inventory is 50.3%. The average years of experience for engineers is 11 and the average score is 40.6%. Engineers performed better at a statistically significant level on 1 of the 30 questions. Students performed better than engineers at a statistically significant level on 12 of the 30 questions. The average score for water resources engineers is 46.8% and non-water resources engineers is 37.4%.<sup>4</sup> The following example shows the patterns of misconceptions in students and engineers.

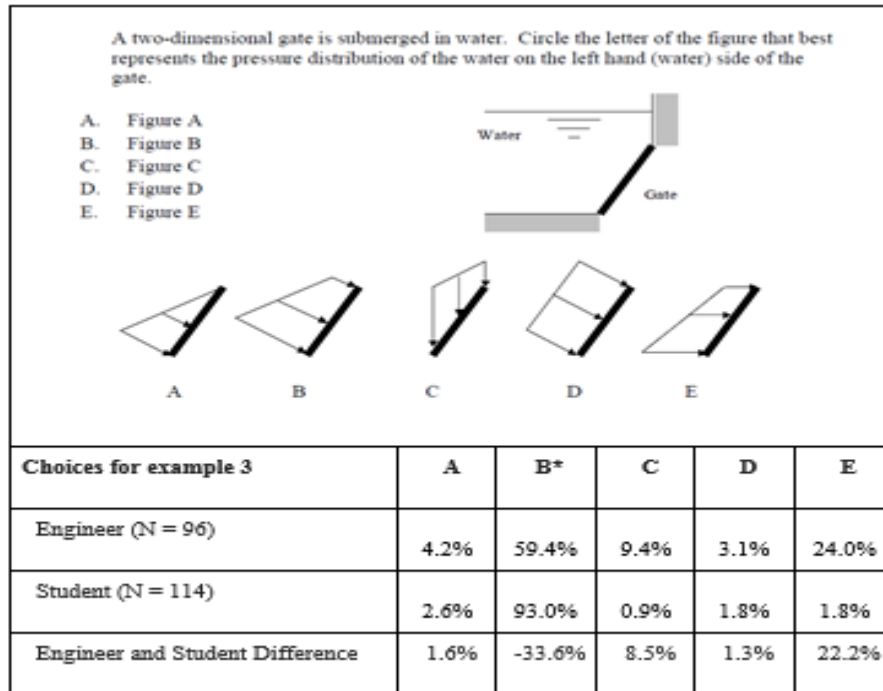


Figure 5: FM Concept Inventory Example 3

### Activity 2: Interviews with Practicing Engineers and Students Using Concept Inventories

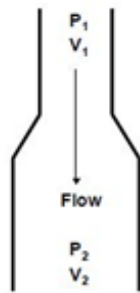
We conducted 29 interviews with civil engineering professionals and 22 with civil engineering students focusing on concepts in Fluid Mechanics. Each interview consists of eight questions from the Fluid Mechanics concept inventory. Four questions focus on velocity and pressure change across a pipe with changing diameter in different flow directions, one question on pressure drop in two identical pipes with different flow rates, two questions on fluid jets and change in momentum, and one question focuses on steady state equilibrium.

### Findings

Student and engineer fluid mechanics concept inventory interviews were analyzed. The average years of experience amongst the engineers is 18.5 years and the average score is 73% with a range of 46% - 100% and a standard deviation of 14%.<sup>4</sup> An example result is shown below.

### Fluid Mechanics Concept Inventory Question

Water flows vertically down through a pipe and enters a section where the cross-sectional area is larger. Viscosity and pipe friction are negligible but gravitational effects are not negligible. Flow is from top to bottom.



What happens to Velocity as water flows from top to bottom?  
What happens to Pressure as water flows from top to bottom?

	Velocity		Pressure	
	Correct	Incorrect	Correct	Incorrect
Engineers	23	6	17	12
Students	16	6	20	2

Figure 6: FM Concept Inventory Question

Students and engineers were asked about the change in velocity in the fluid system shown above. 86% of students and 93% of engineers answered correctly.<sup>4</sup> The misconception among students and engineers was that velocity gain is attained when water flows down to the lower elevation because of gravitational effect. One of the students said:

*“Your velocity is going to ... increase. It has to increase, first it’s going to decrease while going down but it has to, because of flow rate. Then it’s going to increase because of acceleration due to gravity... In this section, velocity due to the flow rate is going to decrease because area increases, but throughout the entire thing, velocity is going to increase due to gravity... My guess is would be that it’s actually velocity increasing the entire time and maybe it increases at a lower rate because of the flow rate.”*

A response from an engineer similarly shows a misconception in reasoning related to the gravitational effect on velocity:

*“Hm. I would say velocity would slightly increase. This is a full pipe coming to this point? ...Okay. And it’s not so tall or deep that it’s going to reach a terminal velocity? Okay. That effect is negligible. In general, I’d say that the velocity would-- wow. I’d say the velocity would increase in this case because of the lack of-- the friction issue...If pipe friction is negligible, but gravitational effects are not negligible, I would say there’s not a change in velocity due strictly to the change in diameter of the pipe, right. Yeah, I’d say there’s no change.”*

Students and engineers were asked about pressure change in the same system. Students performed better on these questions getting 96% correct. Engineers were correct 67% of the time. Students who had an incorrect response for Question 3 related to pressure, exhibited incorrect reasoning about the relationship between terms of the Bernoulli’s equation, as shown in the quote:

*“I want to say pressure goes down... Because you’re increasing your velocity and so you need a corresponding decrease in pressure.”*

Some of the engineers stated that the pressure decreases due to gravitational effect:

*“I would say velocity would decrease and pressure would decrease as well... Because of the gravitational effect, slowing down the--reducing  $V1$  and  $P1$ ...”*

### *Activity 3: Ethnographic Study of Concepts in Civil Engineering Practice*

A graduate student completed a six-month research internship with a large civil engineering design firm to understand how engineering concepts are used in the design process. She worked with a team of about a dozen practicing engineers to design a roundabout. She utilized ethnographic methods, including participation, participant observation, formal and informal interviews, and document analysis to understand how engineers use engineering concepts in the design process.

#### *Findings*

The purpose of Activity 3 was to understand how engineers use concepts in engineering practice. By concept we mean ideas, equations, and relations that are common in undergraduate curriculum, such as sight distance and vertical curve equations. Five themes emerged from the ethnographic data relating concept and context<sup>1</sup>:

#### **Theme 1 - Sequential relationship between project constraint identification and utility of the concept.**

Identifying project constraints preceded the utilization of concepts during the roundabout project. Project constraints consisted of client preferences, minimum standards set by relevant regulating agencies, right-of-way limitations, scheduling, and stakeholder perception. Concept manifestation, such as roundabout and curve geometry, always followed site planning constraints, such as right-of-way limitations and water drainage. Therefore members of the project team utilized explicit transportation engineering design concepts as a means of complying with project constraints. This sequence of identifying constraints in order to focus and guide the discussion and use of concepts in design manifested in all observed activities of this roundabout project.

#### **Theme 2 - Project constraints addressed by contextualizing abstract features of concepts.**

Here “abstract” refers to the visual representation of concepts, such as equations and diagrams, which are isolated from real-world constraints. Features of concepts range from abstract to more contextualized, for example concepts may be represented with generic, universal equations, or could be represented with visual diagrams specific to the project constraints. These more contextualized visual representations of concepts led to discussions justifying design decisions; while more abstract visual representation were used to initiate discussions preceding concrete design decisions. For example, equations were used when settling on singular design decisions; while a superimposed diagram of sight triangles atop a satellite image of the sight were used to justify said design decision. Rather than presenting and justifying this design decision with abstract numerical values, the design team chose to create a contextualized representations of

sight distance by superimposing the triangles atop an aerial photograph of the site in order to display abstract design concepts addressing project constraints.

### **Theme 3 - Social negotiation of meaning expanded individual understanding of the concept.**

The meaning of various concepts were negotiated amongst the design team throughout the discursive acts of the roundabout project. Team members frequently discussed, questioned, and challenged one another's understanding of concepts throughout the design of the roundabout. After members of the design team discussed and negotiated concepts, those team members often purposefully pursued deeper understanding of the concept on their own. These efforts to pursue expansion of individual understanding generally occurred after one's own understanding was challenged by a team member and then this individual level act typically led to resolution of conceptual understanding amongst other team members during the correction of errors and reinforcement of understanding moving forward with design.

### **Theme 4 - Concepts manifested in multiple representations in engineering practice.**

Throughout the roundabout project, it was observed that concepts were not represented in a singular, idealized form, such as might be presented in a textbook. Visual representations of concepts varied depending on the team members engaged with the concept and their available materials, and as equation variables were negotiated the numerical outputs of these equations and associated concept would change. Concepts were often represented in a form that best reflected the understanding of the design team and in the most appropriate manner to meet project constraints. An example of this theme during the roundabout project was a design meeting in which multiple engineers recommended using different volume-to-capacity ratios based on different sources and contexts, such as design standards and seasonal adjustment factors. Volume-to-capacity ratio is typically represented through an abstract equation with a singular numerical solution, but in this design meeting, engineers with different experiential judgment and sources were not able to easily represent this concept in such a singular absolute manner.

### **Theme 5 - Use of material resources efficiently addressed complex processes and problems associated with engineering concepts.**

Throughout the roundabout project, the design team members often relied on tools to resolve certain features of concepts, such as numerical manipulations, rather than engaging in social interactions to find a resolution. Even in social interactions where concepts were negotiated, tools such as design manuals were used to alleviate uncertainty in conceptual representations. Furthermore, reliance on tools was evident in the constant use of computer software to complete abstract conceptual calculations and context-based drawings and simulations. The use of design software, spreadsheets, traffic analysis software, and practical texts were often used to resolve problematic features of concepts in a timelier, more efficient manner than without these tools. When these tools were not able to fully resolve a concept in design, members of the design team would consult other members of the team with experience and sometimes develop their own tool, such as a chart or table, that they could reference in the future to help them utilize these concepts in a more efficient manner. Therefore even though tools are highly utilized in representing concepts, shared knowledge through social interactions is still necessary when tools are less able to handle highly-contextual applications.



#### *Activity 4: Educational Approaches Based on Research Findings*

The research team has evaluated the research results and their implications for the preparation of engineers in the workplace. This evaluation includes consideration of how to address curriculum development, and teaching philosophy to enact change.

#### *Findings*

We have developed an approach to describe how students can learn concepts in ways that represent engineering practice. One of the resulting ideas is that we believe there is some clarity in the multiple roles and representations of concepts that were observed in the design meetings as part of the ethnographic research. Designers had in-depth conversations about concepts and used many different physical and verbal representations. We believe students could learn significantly from observing a real (or staged) design meeting, particularly if it was supplemented with instruction from the teacher. Another pathway to broadening student understanding of concepts is to develop new versions of the concept inventory questions that utilize different representation and/or have constraint based questions. These ideas and others will be published in a forthcoming paper.

#### Discussion:

This project has and will continue to impact engineering education. The results bring into question one of the foundational units of engineering education: concepts and conceptual understanding. Concept inventories often are used formally and informally as the standard of understanding.<sup>2</sup> They are frequently cited in proposals and research papers as being a sound measure to understand the efficacy of educational interventions. Concepts may be considered the core unit of most engineering programs. Curriculum consists of understanding first the concepts of mathematics and science, followed by concepts of engineering. Conceptual understanding is often held above other forms of understanding in our goals to educate engineers. The focus on conceptual understanding and removing, replacing, and repairing misconceptions may have value, but the appropriateness of its position in engineering education is based on many assumptions of student preparation for the engineering workplace.<sup>5</sup> In positioning it at such a high level, we assume that if students just know the concepts, they will be able to apply them in a workplace setting.

Some theories of conceptual change focus on organizational schema where characteristics related to the concepts are the framework of these organizational schemas.<sup>6</sup> Most are cognitive in nature, focusing on the individual. Conceptual change theories are often cited and utilized in engineering education as we attempt to improve educational programs. However, if concepts serve at the discretion of the project and project constraints, then perhaps conceptual change theories can alter their focus in relation to engineering education. This project has questioned approaches that utilize theories of conceptual change, and will lead to approaches that appreciate the nuanced ways of knowing and understanding that are typical in engineering practice.

Results from this research show that students perform better than engineers on most of the concept inventories we examined, and most of the individual questions. Our results showing the multiplicative, diverse and complex ways in which concepts are represented in the workforce

also challenge the education system's focus on concepts. The impact will come as engineering educators think differently about measures and outcomes. For example, are concept inventories a good measure for educational interventions? It is suggested that instead of moving towards measures that reduce concepts to their most singular and simple forms, we move towards measures that include considerations of constraints, and the infinite ways in which concepts can be represented, both in words and in figures and diagrams. Use of such measures would improve the preparation of students to be innovative and efficient practicing engineers. Conceptual understanding and misconceptions may have a place in engineering education, but their prominence is worth questioning, as we strive to improve engineering education programs.

### Conclusion:

About 250 practicing engineers have participated in this research and gained awareness of engineering education research. This exposure has come through taking concept inventories, participating in interviews and ethnographic research in the engineering workplace, and presentations of results. These interactions increase practitioner's awareness of concept inventories, educational research methods, and differences in the role of concepts in academic and workplace settings, and that there is a widespread and continuous effort to research and improve engineering education.

This project will positively impact such educational measurement approaches and techniques in engineering education. A concept inventory can be very valid and reliable, but still not be an appropriate measure to show that students understand what is necessary to engage in engineering design. Results may lead to alternate or revised forms of validity that relate to the practice of engineering. Perhaps measures should be validated with practitioners within the field they relate to. Perhaps measures should start with understandings of noted experts in that field. If practicing engineers perform relatively poorly on concept inventories then other measures may be more suitable to represent understanding in our field. This project will initiate these conversations by disseminating compelling and controversial results related to conceptual understanding.

Our research on the engineering workplace will also contribute to situated cognition theories. We found that concepts serve a secondary role in design; they are used to manage project constraints and are negotiated in the design process. Even the simplest of concepts, like sight distance, are contemplated, argued about, and negotiated in the process. This finding suggests that students need to engage in this authentic negotiation process, rather than the epistemologically naïve process of finding numerical answers to these concepts. Situated cognition places experience and participation and sense making in a community as its foundational units. In our studies of the workplace we found that the project, the characteristics of the project, and the design constraints were the foundational units of understanding. These things are about being an engineer, and the socially situated negotiation that occurs within a space, defined by the people and the project. Engineering education should consider these factors in designing student experiences. Results from this work will foster this discussion, and result in more appropriate means for preparing students for the engineering workforce.

The research completed in this project leads the way for future in-depth studies of engineering practice. This research studied one project in one civil engineering sub-discipline, leaving

potential for several more studies to be done in other engineering disciplines. An exemplar study will allow future researchers to more easily and successfully conduct such studies.

This project can benefit society by building awareness—through data collection efforts and interactions with civil engineers—of the disconnect between education and practice. Knowing that practicing civil engineers perform worse than students in most cases on concept inventory questions challenges the broad role and focus on concepts in undergraduate education. These results can impact other fields that rely on potentially inappropriate and/or non-holistic means of assessment, and encourage consideration of other means of assessment.

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