Assessing the application of three theories of conceptual change to interdisciplinary data sets

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***Abstract*— The study of students' preconceptions and how they affect their learning in science, technology, engineering and mathematics (STEM) fields is of nationally recognized importance. There are, however, various and contradictory theoretical approaches to conceptual change, and none of them have been rigorously applied in the context of engineering education. This paper is part of a larger study drawing on existing sets of data from a wide range of engineering content areas to develop a theoretical explanation of conceptual change in engineering education. In the work reported here we re-analyze students' understanding of concepts about axially loaded members (from mechanics of materials) and Boolean logic (from digital logic). Previously published analyses of these data argue that the context of a problem or question effects students' reasoning about that concept. These contexts can range from the presence or absence of figures or diagrams to the social contexts of the problem. We explored three potential theoretical explanations for the context-sensitivity of student reasoning: (1) a perceptual cues theory, (2) a domain specificity theory, and (3) a language-based theory. It is argued that these competing theoretical explanations do not contradict each other as much as they overlap, and potentially productive syntheses of the theories are proposed as directions for future work.**

Keywords- conceptual change; Mechanics of Materials; Digital Logic

I. Introduction

The study of students' preconceptions and how they affect their learning in science, technology, engineering and mathematics (STEM) fields is of nationally recognized importance [1]. Beyond the agreement to identify and address students' preconceptions, however, there is little consensus about the nature of preconceptions or even what is meant by the term "preconceptions." The progress of empirically based research in addressing these calls depends on a more rigorous description of what is meant by preconceptions, what is meant by learning, and how one interferes with the other.

Within conceptual change research, preconceptions are assumed to be functionally equivalent to accepted conceptions acquired through formal learning, but differ only in content [2, 3]. In this paper, we will distinguish between the acquisition of new knowledge (the creation of new knowledge structures) and conceptual change (changing the substance of preconceptions to accepted conceptions).

In some cases the benefits of new knowledge is obvious, or not strongly contradicted by preconceptions – students' life experiences rarely lead them to doubt that gravity causes an acceleration of 32.2 feet per second per second, for example, so this knowledge is easily acquired. Common life experiences do contradict, however, that an object in motion tends to stay in motion. Learning Netwonian physics therefore requires students to reevaluate life experiences and ways of thinking as well as acquire the individual bits of knowledge being proposed in class (e.g. the equations of kinematics). This type of learning is conceptual change and is typically much more difficult to achieve than acquiring facts like the acceleration due to gravity [4].

Despite overwhelming evidence as to the importance and frustrating lack of conceptual change in traditional education [5], a number of vitally important questions remain contentious and difficult to answer. Why is conceptual change difficult? What are the actual processes that underlie it, and most importantly, what can educators do to promote it in their classrooms? In the past few decades, several theories of conceptual change have been proposed, but none have been clearly superior in terms of their ability to explain observed phenomena or guide instructors in helping their students learn [4, 6]. The development of these theories is typically based on one or only a small number of science disciplines, and few of these published efforts have included engineering concepts or practices [for exceptions see 7, 8, 9]. The purpose of this paper is to contribute to the development of a theory of conceptual change in engineering.

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II. Background

The work reported in this paper is part of a larger effort to utilize existing data to develop and test a theory of conceptual change for engineering education. The data being used consists of more than 250 interviews with engineering students conducted over the past several years in the course of the coauthors' ongoing research programs. These interviews cover engineering topics that include fluid mechanics, geometric highway design, thermodynamics, and a variety of topics within both mechanics of materials and digital logic.

This paper is based on analyses of a subset of those data, specifically interviews about students' understanding of axially loaded members (40 interviews) and Boolean logic (16 interviews). We chose this subset because the methodologies and findings of the interviews addressed a similar fundamental problem, despite being developed separately. In particular, both studies emphasize the ways in which students' reasoning and conceptual understanding seemed to be context dependent – understandings change as the contexts of the interview were changed [10, 11]. For the purpose of our discussion, contexts can be different tasks, presentation styles, or social contexts.

The most prominent theories of conceptual change either do not directly address the context dependence of students' knowledge [12], or they attribute significantly different meanings to it [see for example 13, 14-16]. This question may be more important in the context of engineering education than in the broader field of conceptual change research, because engineers are expected to use the knowledge they gain during formal education through problem sets and examinations in radically different contexts in practice (e.g., design and documentation). Engineering educators in particular need to be concerned with any phenomena that seem to limit students' abilities to apply understandings in new contexts.

The purpose of this study was to develop and test theoretical explanations for why students' understanding of fundamental concepts in mechanics of materials and digital logic seem to be context dependent.

III. Methods

A. Data Collection

As described above, the data used in this study were collected as parts of two separate studies. Results from these studies have been published previously [10, 11]. In both studies, one purpose of the interviews was to present slightly different versions of the same concepts in order to better understand how students' reasoning changed with context. In the interviews about axially loaded members, Brown and Montfort tested context dependence by presenting axially loaded members in multiple ways: two-dimensional schematic drawings, isometric sections, stress elements, and pictures of actual failed concrete cylinders. For the interviews about Boolean logic, Herman et al varied both the social contexts of the problems (e.g., people deciding on pizza toppings or following a recipe to make apple pie) and the specific tasks (e.g., to write a Boolean expression or fill in a truth table). Students were always asked about the same fundamental concepts. For axially loaded members, students were asked about normal and shear stresses, forces and strains. For Boolean logic, students were asked to reason about common operaors including if-then, if-and-only-if, OR, XOR and AND.

B. Analysis

For this paper, we report our reanalysis of the mechanics of materials and Boolean logic interviews. To focus the analysis, we chose to examine students' understanding of one set of concepts from each topic: if-then (implication) and if-and-only-if (bidirectional implication) from Boolean logic and shear force, stress, and strain from mechanics of materials. This narrowed focus allowed for richer descriptions and a more grounded coding of the data to facilitate theory development.

The interviews were primarily analyzed by researchers Dr. Herman and Dr. Montfort who have expertise in conceptual change research. Dr. Herman also provided expertise with digital logic concepts and Dr. Montfort provided expertise with mechanics of materials. Each researcher was a novice in the opposite topic. The primary analysis of each group of interviews was conducted by the novice in that topic. Dr. Montfort analyzed the Boolean-logic interviews that had been designed and conducted by Dr. Herman, while Dr. Herman analyzed the axially-loaded-member interviews which had been designed and previously analyzed by Dr. Montfort. After this preliminary, independent analysis, the researchers compared and discussed codings until agreement was reached.

This novice-led analysis familiarized the novice with the transcripts and technical content of the interviews, but more importantly, it exposed the "expert blindspots" [17] of the content expert. For example, in some cases student statements that had been coded as "incorrect" by the expert in the content area were recoded to be inconclusive due to leading or unclear wording of questions as identified by the novice in that area.

This first stage of analysis, particularly the adjustment of codes to account for blindspots, further emphasized the ways in which students' reasoning appeared to change in different contexts. We conducted a second stage of coding in which the researchers went back to the interviews outside their expertise and searched for patterns and themes [18] in students' reasoning across those questions that had been designed to probe the same concepts. In this use a "pattern" is a grouping of observations. For example, Dr. Montfort identified the pattern that students who referred to "zeros" and "ones" in solving Boolean logic word problems also tended to check their work and successfully identify errors.

The patterns identified were similarly discussed and verified by both researchers before moving to the third stage of analysis. In this stage, the two researchers proposed explanations for those patterns, and sought vignettes in both sets of interviews that supported and challenged those explanations.

We derived three explanations for the differences in student reasoning that we observed in the data. These explanations were developed iteratively through the analysis as opposed to being assumed prior to the analyses. These three explanations will be introduced in the context of the theoretical works that informed and inspired them and supported by vignettes from the data. Although we acknowledge the foundational influence of existing theories of conceptual change on our explanations, we do not intend to be faithful to any existing theories. Rather, we will expand upon their implications in the context of engineering education.

In the reports to follow, students are identified by interview topic and a number: A1 and A2 represent two different students interviewed about axially loaded members, while B1 and B2 represent two different students interviewed about Boolean logic. Note that while each theory is supported by a single student example to allow for sufficient detail, all three theories were developed and validated across both datasets.

IV. Perceptual Cues

The perceptual cues explanation argues that students' use of knowledge is cued by physical perceptual features (e.g., visual or auditory) of the interview that prompt their use of knowledge or reasoning. Building on Minstrell's construct of facets [19] and diSessa's model of conceptual ecology [20], this explanation does not assume that students possess or use coherent domains of knowledge, but rather use pieces of knowledge as they seem relevant or related to the situation. Perceptions cue or activate individual cognitive entities (e.g. memories, facts, beliefs, equations) or strings of common thoughts (e.g. algorithms to solve common problems). In this model, conceptual change is the process of creating more consistent and useful strings of concepts and ensuring that they are cued by all pertinent contexts [21]. Evidence supporting this explanation would be instances where students' reasoning seems directly dependent on what they attend to in the problem set-up. Differences in reasoning would necessarily accompany differences in perception or attention.

A. Supporting Case

When presented with various representations of an axially loaded member and asked if shear stress was present, student A2 sometimes said yes, and sometimes no. Despite the frequency of these questions, and their reoccurrence within only a few minutes, A2 did not appear perturbed by the inconsistency.

A2 correctly identified and reasoned about shear stress when using Mohr's circle (a complex graphical analytical tool relating normal and shear stresses that many students struggle to understand), but she was less able than many students to identify the role of shear in the failure of a concrete cylinder under compression. Many students, even those who struggled to describe shear stress in axially loaded members throughout their interviews, correctly identified the 45° angle of failure (a useful perceptual cue for these students) and associated it with the maximum shear stresses under axial loading. When asked to describe the cause of failure given the same picture, however, A2 reasoned, "…it looks like it has a weakness at an angle in the member sort of like…with the grains this has a failure point but at an angle rather than something straight." When asked "what forces are present and how they are acting," A2 replied, "Well there is a compressive force. So you would have the compressive force acting. So you would have - I don't really understand what you are asking."

In this exchange, we hypothesize that her response to the interviewer's questions about the failed concrete cylinder was cued by the interviewer's description of a "concrete cylinder that failed in compression" and the testing machinery that provided that compression is clearly shown in the pictures. Understandably, then, A2's description of "what forces were present and how they were acting" began and ended with those compressive forces. Furthermore, the rough, pebbly appearance of the failure plane cued her knowledge of "grains" and "failure points," rather than the more abstracted analyses she preferred in earlier questions showing more simplified and idealized members.

Even in reference to the more simplified figures, however, A2's reasoning aligned with the problem features that were most salient to her. When presented with angled, diamond-shaped stress elements (as opposed to the more common square ones oriented parallel to the edges of the page), A2 naturally and easily discussed shear stress in reference to those elements, saying for example that there would be less stress when the elements were oriented that way "because of it being distributed over more surfaces." Reasoning based on the distribution of stress over the "surfaces" of a stress element in this way contradicts the ways stress elements are presented and used in courses, but *is* strongly supported by the visual cues presented in the problem.

A2's reliance on the perceived features of the problem extends beyond shear stress to reasoning about internal and external forces. She would reason using primarily external forces when the figures presented only members with external forces, and primarily internal reactions when those forces were drawn.

B. Challenges

As noted, certain perceptual cues did not always correlate with more difficult tasks. For example, some students were better able to discuss shear in the context of the concrete cylinder, but others were better able to discuss shear in the context of Mohr's circle. In hindsight and after extensive analysis, we can tell that A2 and students who had similar difficulties appeared to envision microscopic components (e.g. "with the grains" or "the fibers") when discussing the concrete cylinder, but these distinctions and patterns would be difficult to identify in the moment or to predict. Although the use of perceptual cues may provide a clean explanation (e.g., "students talk about what they see or hear"), it does not lend itself to predictive power of a students' reasoning ability in a specific context. We identified these themes only after analyzing the interviews several times prior to and during this study.

This theory generates some valuable questions. Why do students fixate on the things they do? Why is A2 so intuitively able to distinguish external and internal forces, but not able to distinguish forces and stresses?

V. Domain-specificity

Building on Vosniadou's "framework theories," [22] the domain-specificity explanation argues that students' reasoning and conceptual understanding is controlled by the domain in which they situate their thinking. The domain of a question, as determined by the student, determines the concepts, procedures, and expectations that are available to be applied. Students identify the domain of a problem based on their perceptions of it. In this model, changes in students' reasoning in response to superficial changes in problem features are caused by shifts in the domain in which the student is acting.

A. Supporting Case

As an example, we will present student B7's apparent understanding of the operator *if-then* in Boolean logic. When first asked, "We're going to be talking about Boolean Algebra. Could you explain the phrase 'IF A THEN B'? How would you describe that in common, everyday English, to a senior who is about to start CS?" he asked, "You mean programming, or more like the logic part?" In this statement, we can see that the student is negotiating which domain to use: the programming domain or the logic domain.

When told to just consider "the logic part," B7 responded with a statement that would be true in the programming domain, but not the logic domain: "Basically, if we have one condition, and we have that it's true, it follows, B. So, if expression A is valued to true, then it follows with B." When asked to write a Boolean expression to show what he meant, B7 wrote a statement in a form of computer programming pseudocode using the words "if" and "then." When asked to write it "with just symbols and variables instead of programming code," B7 wrote "A -> B." In attempting to encourage B7 to elaborate on what he had written, the interviewer suggested ways in which to translate the function into a Boolean expression such as "using a symbol like AND, or OR, and complements," and referring to the specific course that would have covered this material. B7 became frustrated as he was unable to express "IF A THEN B" in any other way:

> **B7:** Well the thing is that, IF A THEN B, there's no AND's and no OR's. IF A; you just write "A." And then, "follows B."
> **Interviewer:** Ok, ok, so what is the relationship between A and B, then?
> **B7:** What?
> **Interviewer:** What is the relationship between A and B, are they…?
> **B7:** Well, B is what happens when A follows to true.

Later in the interview, B7 is asked to express the phrase "if a sandwich has turkey (t) then it must also have cheese (c)" as a Boolean expression (correctly written as f(t,c) = t' + c). He reasoned about the IF-THEN better than many students by noticing, "…it's not saying anything about C whether it has to have cheese[….] Basically what'd we'd be saying now is that we have turkey then there will be cheese, but not necessarily that if we have cheese then we have to have turkey." During this reasoning, however, B7 wrote "c=t" as the Boolean expression reflecting his reasoning, which is what's known as an assignment operation in programming. When asked if "c=t" is a "standard Boolean algebra expression" B7 argues that is by explaining how the operation functions in programming: "C could be expressed as a function and it would be T. So yes."

B7's reasoning and conceptual understanding can best be explained by describing the domains within which he reasons. Initially, B7 is explicitly confused as to the domain of the interviews, confusing computer programming with the more general computer science, and not clearly understanding what the interviewer implies with the phrase "Boolean algebra." Although he tends to use programming terminology, B7 is sometimes clearly aware of the disconnect between the questions and his perceptions of the domain, as evidenced by his frustration with the first line of questioning.

We cannot simply say that B7 is thinking in the "wrong domain," however, because throughout the interview he confidently and adeptly uses many Boolean algebra concepts. Furthermore, B7 had internalized some of the nuances of *if-then.* For example, B7 manages to avoid a common mistake by immediately recognizing that if-then is one directional relationship between the presence of turkey and cheese. This apparent mastery of a difficult concept, however, is immediately juxtaposed by a comparably unusual lack of understanding of how to express the concept in Boolean algebra.

We propose that B7's conceptual difficulties with Boolean algebra are caused by his failure to create strongly defined and distinct domains. Throughout his interview, B7 tries to justify reasoning by appealing to different domains and unknowingly switching between domains. He argues that "c=t" is standard Boolean expression because "C could be expressed as a function and it would be T." While this statement could be a Boolean expression, it unnecessarily appropriates a concept from the programming domain. In other words, B7 lacks the mechanisms to distinguish between two domains and assess the coherence and consistency of his reasoning from the perspective of a single domain. This missing mechanism is most obvious in the first exchange quoted where B7 and the interviewer are apparently unable to make themselves understood. They each understand the components and concepts being applied – *if-then*, A's and B's as variables that can be true or false – but they are speaking about different domains and thus lack the means to interpret each other's statements. The interviewer's repeated questions imply that B7's responses are incomplete or inappropriate, while B7's repetitions of the same phrases imply that he is unable to determine what is missing from his response; he lacks the framework, or domain, to adequately assess the appropriateness of his response.

B. Challenges

Although many students' general patterns of reasoning matched B7's and tended to correspond with questions concerning the domain (e.g. "in programming, or in logic?"), it is difficult to completely separate domain-specificity as the causal agent. Simply put, any differences in student reasoning occur in response to different questions and at different times, and could conceivably be affected by any changes in circumstances including temporary changes in affect, different physical environments, wording of questions or even nonverbal cues from the interviewer. Even if the patterns of domain-confusion continue to co-occur with changes in student reasoning, it is unclear which causes the other. As described above, there is a feedback loop between the ways in which perceptions inform domains and domains inform perceptions. As students change their reasoning in response to different questions, is it because their perceptions are overly mediated by their domain, or because their domain is too limited by their perceptions?

VI. Language-Based

The language-based explanation moves outside the assumption that we can infer students' conceptual or cognitive processes, and instead focuses on the actual data being recorded: student and interviewer use of language. In this definition, language includes any form of verbal, written, or bodily form of expression including drawings, statements or gestures [23]. Instead of assuming that students' *reasoning* or *conceptual understanding* changes when the problem presentation changes, we instead focus on how their uses of language are different or consistent. The use of language includes both the communication of ideas from the participant to the interviewer and the interpretation of the interviewers' statements by the participant.

A. Supporting Case

As an example, we present evidence from student A4's interview about shear forces, stresses, and strains. Throughout A4's interview, he treats forces' and stresses' directions (i.e. in the vertical and horizontal directions or in the X- and Y-planes) as defining descriptions of their fundamental nature. For example, he defines normal forces as "forces on the X-plane." Similarly, he argues for the absence of shear stress in an axially-loaded member by reasoning that "there are no forces in the Y-plane, there are no vertical forces." It's important to note that A4 may not be merely skipping a step in describing a causal sequence, or inferring that "forces in the Y-plane" or "vertical forces" are indications of or causes of shear stress. As indicated by his use of terminology throughout the interview, he apparently treats the statement "there are no vertical forces" as synonymous with "there is no shear stress."

A4 would likely find this discursive tool to be useful in courses that build upon a mechanics foundation, because decomposition of forces into x- and y-components makes up a small but significant portion of the activities students engage in within the context of the course. In much of his coursework, A4 would not even need to be able to discursively distinguish between a force's direction and nature (i.e. normal or shear), because they so reliably correspond. It makes sense then, that he does not make these distinctions in the interview. Unfortunately, normal and shear are not synonyms for X and Y, so this discursive tool has its limits for allowing productive reasoning.

For example, A4 stated that shear stress was present in one axially loaded member, but absent in another when the only difference between the two members was the frame of reference: (in one case the x- and y-directions would align with normal and shear stress and in the other case they would not). Despite being told it was the "same member," A4 made contradictory claims about it within a few seconds.

> **Interviewer**: looking at that top member, are there shear forces present?
> **A4**: No.
> **Interviewer**: And describe your reasoning.
> **A4**: There are no forces in the Y-plane, there are no vertical forces.
> **Interviewer**: And so now, we are making a cut on the same member at cross section BB and just draw the resultant forces and describe what forces are present at cross section BB.
> **A4**: It would be as it comes off perpendicular to BB which also will give it a shear. It should be down.

When discussing forces on the member with a hypothetical non-perpendicular cut in the second set of questions, A4 could discuss the decomposition of the forces into normal and shear components because the relative directions of the forces could be envisioned on a rotated XY axis, and there was therefore no need to distinguish between the direction and nature of the forces.

A4's discursive conflation of "shear" and "vertical" was apparent in his interpretations of questions, as well. Regardless of how a question was phrased, A4 used the terms "shear strain," "shear" and "strain" interchangeably to describe some deformations, again failing to make appropriate distinctions between normal and shear strains, or between strain and stress.

B. Challenges

A primary challenge for this explanation is whether we should distinguish between a students' ability to explain their reasoning and their ability to reason well. For example, a student may have limited ability to engage in discourse about their conceptual understanding in English, but may be able to discourse accurately about their conceptual understanding by making predictions, graphs, figures, or even equations. Does an inability to communicate conceptual understanding with one mode of communication imply that a student possesses detrimental preconceptions? How do we distinguish between different modes of communication and are some more valuable than others for conceptual formation?

VII. Conclusions

Although we pose these theories as three distinct theories, it may already be apparent that there is considerable overlap between these proposed explanations. Considering that each theory was derived from a different, supposedly contradictory, intellectual tradition, we believe that this observable overlap is a finding in itself. Their overlap identifies potentially fruitful areas for future research that build a synthesis of the three theories into a new and more flexible theory.

First, the importance of language holds paramount across all three explanations. Students' perceptions and domains are largely identified by the language they use. Again, this use of the word "language" refers to all the students' efforts at making and interpreting meaning including speaking, drawing, writing equations, and gesturing. Future research in conceptual change, and indeed future efforts to teach for conceptual change, could benefit from closer and more nuanced attention to students', researchers' and instructors' use of language.

Second, the concepts that students struggled to apply in these interviews are often considered fundamental, and their misconceptions are probably directly contradicted in most relevant courses. Small changes in the ways in which problems are presented render many students unable to apply basic concepts, even minutes after they have displayed mastery of them in another context. This supports a well documented trend of low conceptual understanding among engineering students, but adds the potential explanatory factor of highly context-dependent abilities.

Third, all of these explanations go beyond the content itself to examine the contexts in which it is situated, which means the ways in which a subject is typically presented are as important as the subject itself. What is being emphasized, implied and assumed in the typical representations of digital logic or mechanics of materials? Who are the people using these subjects, and what problems are they actually solving with them? Even though they are largely implicit and tacit, these messages are communicated in the ways the subjects are taught.

Finally, we'd like to highlight the ways in which these theoretical differences are important to the practice of engineering education. It is acknowledged that students struggle to lean some aspects of Boolean algebra and axially loaded members, but the response to that problem depends on one's understanding of the cognitive processes underlying it. If students' understanding is limited by their perceptions, the emphasis should be on helping students expand their abilities to link perceptions to pertinent engineering fundamentals. If it is the domain-specificity of their understanding that is problematic, then explicit instruction about the boundaries, purposes and history of the subject should help. If it is rather a problem of language, then treating learning as language acquisition could facilitate conceptual change. Without an empirically based and tested theory of conceptual change in engineering education, it is difficult to even define the problem, let alone begin to solve it.

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