What is Engineering Knowledge: A Longitudinal Study of Conceptual Change and Epistemology of Engineering Students and Practitioners

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Introduction

Conceptual change and personal epistemology are two educational development frameworks that have had limited application in the sub-field of engineering education and could provide new and insightful ways of understanding engineering student development. Tracking the development of conceptual understanding and the associated changes that students experience can provide a plethora of information on what concepts are truly difficult for students as well as what concepts engineers continue to use as they transition into the workplace. Tracking student epistemological development can provide needed insight into the beliefs that students hold about engineering knowledge, how those beliefs relate to student understanding and success and how those beliefs and their relationship to understanding change as students progress through school and transition into the workplace.

Goals and Objectives

The purpose of this project is to determine when conceptual and epistemological changes occur for engineers on the path from undergraduate-student to early-career, practicing engineer. The project is also designed to explore how these changes occur and how they interact with each other. In order to achieve this purpose, we are tracking two cohorts of students; one between their sophomore year in college and graduation and the other between graduation and their second year as a practicing engineer, The two specific aims of this project are: (1) model the development of student and early-career engineer epistemology and conceptual understanding of civil design concepts, and (2) identify key conceptual and epistemological changes that challenge early-career engineers.

The specific research questions of this project are:

1. How do engineering students change conceptually and epistemologically during the course of their undergraduate education?
   a. Which previous student beliefs and ways of thinking are the most resistant to change and interfere the most with learning?
2. How do early-career engineers change conceptually and epistemologically during the course of their first 2 years of practice?
   a. How do the changes inspired in undergraduate engineering programs help or hinder engineers through their first 2 years of practice?
   b. How do engineers use the engineering content (laws, equations, computational skills, understanding of fundamental phenomena) they remember?
3. What conceptual and epistemological differences are there between the sociocultural contexts represented in our sample?

Activities

Participant population
There are two cohorts of participants. Cohort 1 has a total of eleven participants. Of these eleven participants, two are female, ten are part way through their junior year in Civil Engineering and one is beginning the junior year in the Civil Engineering program. Two of the junior level participants have completed previous, unrelated bachelor’s degrees, three have completed previous associate’s degrees, one transferred into the program from another university and the remaining students started their academic career at WSU. Cohort 2 consists of 18 participants, 16 of which are currently employed in engineering-related jobs. Of these 18 participants, four work as project engineers in construction firms, three work as designers for public utilities, two are completing summer school, and the remaining nine work as EIT’s in engineering firms. Six are female and 12 are male. Thirteen of them work in the state of Washington, while the others work in California, Texas and Minnesota. Outlines of the sample selection process are given in Figure 1 for Cohort 1 and Figure 2 for Cohort 2.

![Diagram](image-url)  

Figure 1. Cohort 1 sample selection protocol.
Both weekly check-in interviews and one extensive interview are completed with each participant per semester. Check-in interviews with Cohort 1 students began in Fall 2011. Two-hour long extensive interviews were completed with Cohort 1 participants at the end of both the Fall 2011 and Spring 2012 semesters, for a total of two extensive interviews per participant. Cohort 2 participants have been similarly engaged in both check-in and extensive interviews. Cohort 2 participants engage in check-in interviews approximately once every two weeks to facilitate their participation around their work schedules. They have also participated in two extensive interviews, one in Winter 2011 and the other in early Summer 2012. More than 400 check-in interviews and 75 extensive interviews have been conducted.

Check-in Interviews

The weekly or bi-weekly check-in interviews begin with very open-ended questions intended to allow the participants to freely reflect on the previous one or two weeks and to allow researchers to collect participants’ socio-cultural data. During each check-in interview, Cohort 1 participants are also asked to work an example problem while explaining their reasoning. These problems have either been taken from curricular materials (such as textbooks, homework sets or exams) from courses the participants are currently enrolled in or brought in by participants as examples of problems that have been particularly challenging for them to work on. This ability to help dictate the content of the interviews and work through problems that are currently challenging them creates an environment of reciprocity in the interview process and, we believe,
will reduce attrition through active engagement\(^1\). Additionally, the difficult problems provide critical insights into the concepts students are having difficulty with. In the weekly check-ins, Cohort 2 participants are asked to recall an engineering problem they faced in the previous two weeks, and explain their approach to solving it. The personal epistemology aspect of the check-in interviews for both cohorts is addressed through follow-up questions as the participants are talking about the engineering problem they are working on. This method of addressing personal epistemology guarantees a specific domain (i.e. the specific topic area of the problem) for the responses about students’ knowledge beliefs, which has been shown to provide necessary context for these responses\(^2, 3, 4\).

**Extensive Interviews**

The extensive interviews are approximately two hours long and are divided into roughly an hour of questions focused on conceptual change and an hour focused on personal epistemology. Although both portions follow a clinical interview format\(^5\) in order to effectively draw out and assess student understanding, they do not contain the same content. The conceptual portion is divided into two halves, one focused on an issue related to mechanics of materials and the other focused on an issue related to fluid mechanics. The personal epistemology portion is divided into two portions as well. The first is a domain-specific personal epistemology section that asks participants to respond to specific statements related to dimensions of personal epistemology within the domain of Civil Engineering. This allows us to determine the engineering personal epistemology stances of each participant. The second portion of the personal epistemology section uses ill-structured problems\(^6\). Each participant is asked about an ill-structured engineering problem that helps us further define their personal epistemology stances.

Extensive interviews have been implemented in Fall 2011 and Spring and Fall 2012. Each interview had different conceptual problems, different ill-structured problems, and a progressively improving set of personal epistemology questions. None of the conceptual problems required participants to recall equations or run calculations. Problems are not oriented toward calculations in order to get a true assessment of participants’ conceptual understanding. When participants are required to explain their reasoning without simply being able to ‘plug and chug’ it is much easier to see what concepts they struggle with the most. The interviews focus on three main questions about engineering concepts:

- What are they? – This question allows us to assess participants’ understanding of the classification of concepts. More detail on this question is given in Figure 3.
Figure 3. Detail on assessing participant understanding of what engineering concepts are.

- How are they used? – This question allows us to assess whether participants understand how and when to implement engineering concepts. More detail on this question is given in Figure 4.
What do they do? – This question allows us to assess whether participants understand what given engineering concepts can be used for. More detail on this question is given in Figure 5.
Figure 5. Detail on assessing participant understanding of what engineering concepts do.

<table>
<thead>
<tr>
<th>Overarching Topic</th>
<th>Subtopics</th>
<th>General Questions</th>
<th>Sources of Information</th>
<th>Specific Probes</th>
</tr>
</thead>
<tbody>
<tr>
<td>What do they do?</td>
<td>Role in design</td>
<td>What engineering problems is this important to?</td>
<td>Probes during conceptual questions</td>
<td>Do real engineers care about this?</td>
</tr>
<tr>
<td>Causes</td>
<td>Is it designed, or do designs need to account for it?</td>
<td>Probes during conceptual questions</td>
<td>How could you change it?</td>
<td></td>
</tr>
<tr>
<td>Effects</td>
<td>What does it relate to?</td>
<td>Probes during conceptual questions</td>
<td>What if you wanted to...?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>What does it cause?</td>
<td>Probes during conceptual questions</td>
<td>What causes it to happen?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>What does it impact when it happens?</td>
<td>Probes during conceptual questions</td>
<td>What impacts they way it happens?</td>
<td></td>
</tr>
</tbody>
</table>

Ranking tasks from previous work:
- What does it cause?
- What does it impact when it happens?
A summary of the extensive interview content is provided in Table 1.

**Table 1. Summary of extensive interview content.**

<table>
<thead>
<tr>
<th>Extensive Date</th>
<th>Conceptual Understanding</th>
<th>Personal Epistemology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solid Mechanics</td>
<td>Fluid Mechanics</td>
</tr>
<tr>
<td>Fall 2011</td>
<td>L-shaped building with</td>
<td>Pressurized drinking</td>
</tr>
<tr>
<td></td>
<td>wind load</td>
<td>water system</td>
</tr>
<tr>
<td>Spring 2012</td>
<td>Crane near capacity</td>
<td>Open concrete river</td>
</tr>
<tr>
<td></td>
<td></td>
<td>channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall 2012</td>
<td>Concept inventory</td>
<td>Concept inventory</td>
</tr>
<tr>
<td></td>
<td>questions</td>
<td>questions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>

The Fall 2011 interviews focused on conceptually identifying issues and concepts related to a system including an L-shaped building under a wind load and another system of pressurized pipes in a residential water system. In the L-shaped building system, participants were asked to predict the behavior of the building under a wind load. This could include describing movement, the path the load would travel, locations of stress concentration, and likely points of failure. It is important to note that this could include those concepts; participants were asked about the system with limited reference to key terms from their engineering courses (e.g. stress, deflection, failure) so their responses were dictated by their understanding of the relevant concepts. In the pressurized pipe system, participants were asked to explain behavior in the system in terms of issues like pressure, velocity and energy and also asked questions that delved into their understanding of demand in such a system. An example of a Cohort 1 participant response in this section is:

**Interviewer:** Okay. So where would you expect the highest pressures in the system?

**103:** Well, highest pressure I would expect right there as it exits the reservoir. And then as it goes, six-inch pipe’s going to be less restrictive. Kind of think of it as electricity. It’s got less resistance than four and two inch. So then it’s going to flow to here. Most of the water pressure’s going to-- this line here, since it’s four inch, it’s going to have a higher flow through it. So it’s going to, I would think, have more pressure. This is more restrictive. That will cause the pressure to be less. Then they’ll meet up here, and that’ll be kind of like the sum or the result of both pressure come together again.

The ill-structured problem asked participants to weigh issues of precision and error in engineering systems.
The Spring 2012 extensive interviews focused on issues and concepts related to a system involving a construction crane and another involving an open concrete river channel. In the construction crane system, participants were asked to identify issues related to failure of the crane as well as issues when both live and lateral loads were applied. This could include describing concepts related to failure, importance of material, and types of loading resulting from the applied loads. An example of a Cohort 1 participant response in this section is:

Interviewer: Okay. So I think you started out by saying there were some things about the river that you wanted to know?

107: Yeah. So I probably want to know how high the river gets at peak season, if there's any runoff from, you know, the higher parts of, you know, the geography, if there's any, like, snow melt that comes down, if there's a bunch of, like, I know, in some rivers, like, where I'm from, there's a bunch of debris that comes down after fall where the rivers just get so overloaded with, like, broken down trees and rocks and what have you. And I'd want to know if there's a lot of crap, basically, coming through because I'd obviously need to think about that. Maybe that's why they're kind of putting a channel in. But let's see. I'd also- I'd probably want to know kind of the steepness of the river, if, you know, the town's basically on a hill or if it's kind of flat. I'd also want to know how much water comes in and adds to, you know, this amount of water or this amount of water, will they all converge together?

In the open channel system, participants were asked to explain the behavior of water in a channel system and the effects of a concrete channel section on a natural river system. The ill-structured problem asked participants to explore the idea of bias in engineering.

The Fall 2012 extensive interviews focused on conceptual problems drawn from existing concept inventories. The solid mechanics section was drawn from the solid mechanics concept inventory developed by Richardson and Morgan. These questions focused on issues of normal and shear stress in axial and bending members, as well as in combined loading problems. The fluid mechanics section was drawn from the fluid mechanics concept inventory developed by Martin et al. These questions focused on issues of pressure, velocity, and flow in pipe systems and open containers. For both of these sets of questions, participants were given time to select an answer and then asked to explain their reasoning. The ill-structured problem asked participants to explore issues related to managing natural systems as an engineer, particularly the water cycle and its management and use by society.

Because the domain-specific personal epistemology section deals explicitly with participants’ personal beliefs, we felt that the most effective method of data collection would be to continually improve the questions and method of asking rather than develop a new set of questions for each extensive. By the end of the study, we hope to have an effective and well-supported tool for assessing personal epistemology. It is also possible that this tool, with continued research, will be able to be converted into a survey of personal epistemology.

During the first extensive, we developed a set of statements that represented personal epistemology stances predicted by previous researchers theories. Each of these stances could be classified into one of the dimensions of personal epistemology that we are using as our
Theoretical framework. These dimensions are structure of knowledge, source of knowledge, certainty of knowing, justification of knowledge, and social processes of knowing. The dimensions were developed based on those set forward by previous researchers and summarized by Hofer and Pintrich\(^3\). Each of the dimensions and examples of how we addressed them are given in Figures 6 through 10. Participants were then asked to agree or disagree with each statement and explain their reasoning. During the second extensive, an interactive portion was added to this method and the statements were improved based on analysis of participants’ responses and reactions to the previous set of statements. The interactive portion of this section required participants to place a card for each statement in one of three categories, either agree, disagree or a third category of their definition (usually ‘maybe’ or ‘unsure’) before explaining their reasoning. The statements in this section have continued to go through a revision process with the analysis of each consecutive extensive interview set.

<table>
<thead>
<tr>
<th>Epistemological Dimension</th>
<th>General Questions</th>
<th>Source of Information</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure of Knowledge</td>
<td>How is knowledge structured, in terms of the relationships between concepts?</td>
<td>Probes During Conceptual Questions</td>
<td>Probes during conceptual questions about learning: like is it easier to go after big concepts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Epistemological Interviews</td>
<td>Is that just your way of thinking about it, or is that always the way it is?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Probes during ill-structured problems</td>
<td>Something about memorized facts versus laws...</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Are there always big concepts underlying problems?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>From King and Kitchener</td>
</tr>
</tbody>
</table>

Figure 6. Detail on the Structure of Knowledge dimension.
Figure 7. Detail on the Source of Knowledge dimension.
Figure 8. Detail on the Certainty of Knowing dimension.

Examples

<table>
<thead>
<tr>
<th>Source of Information</th>
<th>General Questions</th>
<th>Epistemological Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Questions</td>
<td>How certain can knowledge be in use?</td>
<td>Certainty of Knowing</td>
</tr>
<tr>
<td>Epistemological</td>
<td>Probes during Conceptual Questions</td>
<td>How certain can knowledge be in use?</td>
</tr>
<tr>
<td>Interviews</td>
<td>Epistemological Interviews</td>
<td>Will x always be like that?</td>
</tr>
<tr>
<td>Probes during Ill-structured problems</td>
<td>From King and Kitchener</td>
<td>How sure can you be that that is right?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Are there other approaches to that problem?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If Manning had died would someone else have made the same thing?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Is it common for questions to have lots of ways to get to the answer?</td>
</tr>
</tbody>
</table>

Figure 8. Detail on the Certainty of Knowing dimension.
Figure 9. Detail on the Justification of Knowledge dimension.
Data Analysis

Analysis so far has focused on the development of narratives for each participant as well as coding and thematic analysis of the extensive interviews. The development of narratives began by analyzing students’ first extensive interview and comparing it to the following extensive interviews and intermediary check-in interviews. For each interview, the participants’ conceptual understanding of mechanics of materials and fluid mechanics are characterized based on their approach to the problems and the knowledge they use to explain their reasoning. Their personal epistemologies are characterized according to the stances they take on the following dimensions: structure of knowledge, source of knowledge, certainty of knowledge, justification of knowledge and social effects on knowledge. These dimensions were developed by the research team based on those defined by Hofer and Pintrich. Once the extensive interviews for each participant are characterized in this way, the second extensive interview is compared to the first to look for changes in conceptual understanding and personal epistemology. The narratives for each participant are then filled in with details from their check-in interviews. Future analysis will look for patterns in how features of the participants’ experiences (as revealed in their check-in interviews) relate to changes in their conceptual understandings and personal epistemologies.
**Future Activities**

Data collection on this project is expected to continue with most participants until spring 2014. Because of the inconsistencies across student backgrounds, some of the Cohort 1 participants will graduate in fall 2013, some in spring 2014 and some in fall 2014. All participants will continue to participate in weekly check-ins as well as extensive interviews until spring or fall 2014. This will provide an anticipated additional 12 hours of weekly check-in interviews per participant and approximately six hours of extensive interviews per participant after the conclusion of the fall 2012 semester. These data will continue to be analyzed thematically to identify the personal epistemology stances of participants as well as their current conceptual understanding in both solid and fluid mechanics. The themes identified for each participant will then be incorporated into the narrative of their development.

Results from the current and continued data analysis are being or will be written up for publication. Currently, results from the first year and a half of data collection are being assembled into a journal-length paper on the personal epistemology of Cohort 1 participants. The continued publication of our results in both academic journals and conferences will allow us to disseminate pertinent findings to the community at large.

**Preliminary Findings**

Graduating seniors’ conceptual understandings and personal epistemologies are highly varied. Overall though, they appear to be more developed (in regard to conceptual understanding) and more open to uncertainty (in regard to personal epistemology) than sophomore engineering students. That said, the full range of personal epistemologies (as defined by scholars like [9] or [10]) and conceptual understanding appears in each cohort. Some sophomores are more open to uncertainty than some graduating seniors, for example.

Individual differences apparent in open-ended, longitudinal data collection suggest that traditional survey-based instruments may not adequately capture many individuals’ personal epistemologies. The interpretation of key terminology (e.g. truth, reality, certainty, knowledge, and understanding) seems highly sensitive to the context and perceived goals of the interviewer. In some cases participants simply lack the pertinent jargon. For example many discussions rely on the imprecise differentiation between something that is “true” and something that is “true-true.” What is meant by “true” and “true-true” appear to vary among students. One student might take “true-true” to mean objectively true in all cases, while another might take it to mean pragmatically useful and therefore of adequate truth regardless of its basis in reality. This is particularly problematic because the distinguishing of objective and pragmatic truth is often the primary use of the “true-true” terminology. In other words, many students attribute nearly opposite meanings to centrally important terminology.

Additionally, participants’ personal epistemologies appear to be very strongly influenced by domain. In many cases, participants are aware of these differences, for example pointing out that their expectation of simple answers is unique to engineering, but in some cases they are not. When participants discuss epistemological stances from different domains without noticing (which occurs often as they bring up different examples to support their statements), they often contradict themselves.
There are regular patterns in students’ conceptual difficulties. Most recent graduates were largely unable to qualitatively analyze simplified real-world situations involving fluid and solid mechanics. In other situations:

- In solid mechanics, participants struggled to identify the types of stress that would result from a particular loading and believed that internal forces and stresses could only be identified through measurements.
- In fluid mechanics, participants relied on direct relationships between velocity and whichever flow property was inquired about.
- Students with relevant work experience were more able to answer the interview questions and more comfortable doing so. In this case, “relevant” refers only to the broad category of engineering – “structural engineering” for example – rather than any specific commonalities between their work experience and interview questions.

Most sophomore engineers also struggled to qualitatively analyze situations involving fluid and solid mechanics, and often also struggled to quantitatively analyze these situations.

- In solid mechanics participants struggled with core concepts like moment of inertia and internal vs. applied forces. Few students were able to consistently differentiate qualitatively between internal and external forces.
- None of the students had yet taken any courses on fluid mechanics outside of basic physics. As a result, students currently have limited understanding of fluid mechanics and consistently fall back on half remembered formulas relating velocity and pressure to analyze situations relating to fluid mechanics. These students had very limited willingness to address these situations qualitatively and often struggled to do so.
- As these students have progressed from Statics through the Mechanics of Materials course, their apparent change in understanding of the concepts of solid mechanics has varied widely across the sample population. This is particularly apparent when situations that require them to address assumptions or simplifications arise. Some students seem more able or willing to recognize and apply assumptions and simplifications when analyzing solid mechanics situations than others. These other students often appear to have limited or no recognition or understanding of the underlying assumptions and simplifications they apply during analysis.

Conceptual understanding was mostly seen as divorced from success at work for newly hired engineers. Familiarity with the workplace, office policies, pertinent regulations and construction practices were all cited as more important than conceptual understanding of related processes. As an exception, two participants already heavily engaged in design activities cited conceptual components as important in their work several times.

Work experience appears to vary significantly at the individual level. Two participants working at the same office and hired a week apart had nearly opposite experiences in terms of office supportiveness, feelings of adequacy to perform the work asked of them, perceptions of the value of their work, and even the logistics of how they were introduced to and integrated into the office.
For new engineers, experience is seen as the best (and sometimes only) source for new knowledge because that knowledge is seen as extremely context specific and therefore very diverse and broad. These engineers do not perceive significant underlying patterns or themes, but rather a list of circumstances or problems that each have a characteristic solution approach that can best be learned through experience or asking someone who has experience. Verbal exchanges are valued much more highly than written ones for learning, so much so that written information is sometimes not considered a valid resource.

Outcomes and Publications

There have been several outcomes and dissemination efforts working toward accomplishing the purpose of this study. For example,

- Narratives of ongoing student conceptual and epistemological development have been produced;
- Engineering students and beginning engineers’ personal epistemologies have been characterized at two stages in time;
- Engineering students and beginning engineers’ conceptual understandings of fluid mechanics and mechanics of materials have been characterized at two stages in time;
- Nearly 200 hours of audio and over 400 written pages of data have been collected through semesterly, semi-structured extensive interviews and weekly, loosely-structured check-in interviews, as well as a collection of difficult engineering problems faced each week by both engineers and students;
- Results and analysis of the previously stated items have been, or will be, published through two conferences and include:

Significance

Matching the predicted changes in the field of engineering to a more competent and innovative workforce requires fundamental changes to our approach to engineering education
The research described here will not only help educators by identifying some of the significant learning challenges their students face, but by laying the groundwork for a better understanding of the unique processes through which students become engineers. It is unclear why and how conceptual and epistemological changes occur in some cases and not in others, and how these changes, or lack thereof, relate to particular problems engineering students face. Understanding how engineering students develop conceptually and epistemologically into practicing engineers is an essential step in the move toward better preparing engineering students for the unpredictable future workforce. This research will provide engineering educators and practitioners with road maps of students’ conceptual and epistemological changes through their second year as practicing engineers, allowing them to more efficiently and effectively prepare students by targeting concepts and epistemological beliefs of key importance. Students whose conceptual and epistemological changes have been primed in their undergraduate careers will be better prepared to undergo further changes as practicing engineers, and will more quickly be able to adapt to the workforce and be successful.

Acknowledgements

This material is based upon work supported by the National Science Foundation under the Division of Engineering Education and Centers Innovations in Engineering Education, Curriculum, and Infrastructure Program, Grant No. 1025205. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

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