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Secondary Students' Conceptual Understanding of Engineering as a Field

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Abstract

Researchers have long been interested in how to recruit and retain more and more diverse students into engineering programs. One consistent challenge in this research is understanding the impacts of interventions from the point of view of the student, and how their preconceptions may influence that effectiveness. This study investigated how secondary students understand the concept of engineering, including what engineering is and what engineers do. The purpose of this work was to describe students' conceptions of engineering, and to determine how those perceptions relate to student interest in engineering careers. The investigation was founded on the theoretical framework of conceptual ecology. Students from one high school that are typically underrepresented demographically in engineering programs were interviewed about their perspective on engineering. Interviews were transcribed and analyzed using the constant comparative and thematic analysis methods. Students who were interested in pursuing an engineering career generally believed that it involved hands-on building or fixing of cars, bridges, or airplanes. Students who were not interested in a career in engineering discussed a broader variety of types of engineering, and more often cited altruism and inherent interest as reasons that others would pursue such careers. Most students in this study did not express very complex or rich conceptions of engineers or engineering, but their conceptual ecologies suggest that they would be resistant to changing these conceptions. This suggests that recruitment and retention programs will need to directly address students' existing conceptions of engineering.

Keywords: conceptual understanding, engineering careers

Introduction

Retention and recruitment of diverse and talented individuals into the engineering industry is a topic of long and increasing interest. Research investigating why students choose to discontinue science, technology, engineering, and mathematics (STEM) majors has indicated that students' perceptions of engineering as a career play a major role in persistence decisions (Seymour & Hewitt, 1997). Research has shown that these conceptions change over students' college careers (Chachra, Kilgore, Loshbaugh, McCain, & Chen, 2008; Jocuns, Stevens, Garrison, & Amos, 2008), but students of all ages and stages often have great difficulty communicating or defining what the discipline of engineering encompasses (Chachra et al., 2008). Additionally, there is a line of research suggesting that many students who leave engineering do not

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understand it as a field in the same way that educators, practicing engineers, or other experts do (Seymour & Hewitt, 1997). In other words, secondary students rarely know what engineering is, or what engineers do.

Investigations of secondary students' career choices have understandably focused on social constructs such as self-efficacy as important influences on career choice (Savelsbergh, de Jong, & Ferguson-Hessler, 2011). For example, Bandura et al. write that "…socioeconomic, familial, academic, and self-referent influences operate in concert to shape children's career trajectories," (Bandura, Barbaranelli, Caprara, & Pastorelli, 2001, p. 198). In this paper the authors lay out strong empirical evidence for the importance of self-efficacy in determining career choice, writing, "The patterning of children's perceived efficacy influences the types of occupations for which they believe they have the capabilities, which, in turn, is linked to the kinds of career pursuits they would choose for their life's work," (Bandura et al., 2001, p. 198). In comparing their own "capabilities" with their perceptions of a career children are making use of their conceptual understanding of that career: a mental representation of what the career is and how it fits in with the rest of the world as they understand it. In this way, research on young students' conceptual understanding of careers acts in concert with self-efficacy and the other socio-cultural or affective constructs that career choice research has identified as affecting career choice.

There are increasing efforts to educate secondary students about engineering. These efforts are often motivated by the widely cited findings that students who leave engineering may actually have the potential to become very capable and contented engineers: Seymour and Hewitt (1997) write, "In describing the nature of work available to graduates, switchers in all S.M.E (science, math, and engineering) majors drew upon a set of myths and stereotypes," (p. 188). For example, many students who left engineering (or other science-related majors) felt that their careers after graduation would primarily involve working alone on technical problems. This belief is in direct conflict with both current definitions of engineering (for example, as exemplified in ABET's 2011 accreditation criteria that engineering graduates have the abilities to "communicate effectively" and "function on multidisciplinary teams") and predictions about how the field will need to change (National Academy of Engineering, 2004). Additionally, Seymour and Hewitt (1997) also note that many students who leave engineering or science-related fields do so because they originally misunderstood the field.

The focus on marketing engineering (National Research Council, 2008), or understanding the conceptual content of engineering (Custer, Daugherty, & Meyer, 2010; Daugherty, 2011) has somewhat deemphasized the role of secondary students' understanding of engineering in determining their responses to designed interventions or their motivation to learn engineering concepts. The purpose of this study is to describe how a group of high school students understands engineering as a field, with a particular emphasis on how that understanding might affect education efforts.

Background

Conceptual Understanding

Halloun and Hestenes'(1985b) landmark Force Concept Inventory first identified the pervasive and powerful effects of students' "commonsense beliefs" on their learning. Their thesis, which has since inspired an entire field of inquiry into students' "conceptual understanding" of various topics, is that students begin the study of physics with an existing set of commonsense beliefs about why the world works in the way it does (Halloun & Hestenes, 1985a). Students do not begin the study of physics (or biology as seen in Bishop and Anderson, 1990, chemistry as seen in Sandoval, 2003, engineering as seen in Streveler, Litzinger, Miller, and Steif, 2008, history as seen in Bandura, Barbaranelli, Caprara, and Pastorelli, 1996, mathematics as seen in Sandoval and Çam, 2011 or computer science as seen in Sarewitz, 2004) with a blank slate to be written on by lectures and textbooks. Instead they have an intuitive sense of how the world works in that arena, and interpret all new information through the lens of that sense (Sarewitz & Pielkejr, 2007; Vosniadou, Vamvakoussi, & Skopeliti, 2008). This filtering explains, to a large degree, why some concepts are so much more difficult to learn than others. Students' struggle to remember that force causes acceleration not because $F = ma$ is a complex or difficult formula, but because their commonsense understanding of the world emphasizes velocity over acceleration (Trowbridge & McDermott, 1980, 1981). This is true of any topic, and is the fundamental proposition of the constructivist approach to learning (Bransford, Brown, & Cocking, 2000). It is logical, then, to expand the idea beyond academic concepts into other concepts that make up learners' worlds, such as their understanding of potential career fields. As shown in the example of conceptual change in history (Limón, 2002), even broad assumptions about the world such as the relative orderliness or stochasticity of human history can be developed through life experience, and then applied (sometimes inappropriately) to new concepts.

Beyond the fundamental interest of such topics for cognitive science, one area of emphasis in conceptual understanding research is how it affects learning. When learning requires fundamental changes to an individual's conceptual understanding, it is referred to as conceptual change and is often much more difficult to achieve than other types of learning (Chi, 2008, 2009). Conceptual change theorists have proposed several explanations for why some learning is much easier than others (see diSessa, 2008; Ozdemir & Clark, 2007 for summaries). These theories generally explain the difficulty in terms of how the new information contradicts existing cognitive structures

(Chi, 2005; Chinn & Brewer, 1993), or past experiences (diSessa, 1993; diSessa & Minstrell, 1998).

Theoretical Framework

Although there is broad consensus on the importance of students' previous beliefs, there is a great deal more diversity in how researchers have chosen to characterize them (see Ozdemir & Clark, 2007 for a summary). Conceptual ecology (Strike & Posner, 1985, 1992) is one such theoretical approach to conceptual change that focuses on the interactions between individual concepts and how and why new concepts may fit within existing frameworks, with specific criteria defined characterizing why some concepts may be rejected or accepted. For example, a concept must be plausible to be accepted. Because this study is an exploratory effort intended to support and contribute to future lines of inquiry under multiple theoretical frameworks, the conceptual ecology approach was chosen to guide it.

Generally, the idea of a conceptual ecology draws on the constructivist theory of learning which posits that learning takes place when individuals form their own understandings, and is therefore strongly affected by the content and organization of individuals' existing knowledge (Bransford et al., 2000; Bruner, 1960). Conceptual ecology represents an attempt to explain the interaction of existing knowledge and new information metaphorically as a dynamic ecosystem (Posner, Strike, Hewson, & Gertzog, 1982). In a natural ecosystem all the organisms, processes and resources are balanced and fit together. When a new entity is introduced (for example a new organism, or a new inflow of nutrients), a complex chain of events can lead to any of a number of outcomes including no basic change (for example if the nutrients are simply transported through the system), small change (for example if the new organism replaces another organism and fills the same ecological role), or drastic change (for example if the new nutrients cause algal blooms and drastically change the ecosystem). Learning is pictured as the introduction of new cognitive entities to an already complexly interacting ecosystem of information, experiences, assumptions, and related conceptual systems (Strike & Posner, 1985). The same basic types of responses to new elements apply in conceptual as natural ecologies; the new cognitive entities could replace existing entities, be outcompeted, or find a new, unexpected niche in the ecosystem.

Just as organisms, processes and resources are all equally important features of natural ecosystems, conceptual ecologies are constructed of various forms of conceptual entities. The various types of knowledge include memories, concepts from other fields, fundamental assumptions about knowledge and the universe, perceptual schema, and organizational conceptual hierarchies. The diversity and complexity of conceptual ecologies is no less important or bewildering than that of natural ecosystems.

Strike and Posner (1985) propose seven diverse types of cognitive entities that may exist in a conceptual ecology, described in Table 1 below. Not all types of cognitive entities are expected to be significant in any particular conceptual ecology. For example, in the present study exemplars, analogies and other knowledge were considerably more at the forefront than other the other types of cognitive entities.

Although the list presented in Table 1 is not intended to be definitive, it provides a useful means of referring to different types of cognitive entities. The important theoretical foundation of this research lies in the variety of types of cognitive entities that exist, and how they interact within a conceptual ecology. This wide-net approach is important in this exploratory study because students' beliefs about engineering are largely unknown.

Engineering as a Concept

Conceptual understanding research typically concerns students' understandings of physical phenomena. Although conceptual change research has been performed in social-science fields (e.g. Limón, 2002), the conceptual approach is appropriate to the study of students' understandings of what engineering is and what engineers do. In terms of the constructivist approach to learning, there is no fundamental difference between the concept of "engineering" and science concepts such as "force" or "gravity." In both cases supposedly naïve students enter the classroom with a lifetime of experience engaging with the observable influence gravity (though they may not attribute them as such) and the products of engineering such as roadways, machines and bridges (though they may not attribute them as such). Students learn about all these concepts by

Table 1
The seven proposed "cognitive resources" most important in a conceptual ecology in terms of conceptual change. Adapted from Strike and Posner (1985).

Cognitive entities	Explanation
Anomalies	Failures of existing concepts to explain experiences or data
Analogies and metaphors	Explanations of new ideas made from older, more understandable ideas
Exemplars and images	Prototypical examples of things or mental models of processes that affect "a person's intuitive sense of what is reasonable" (p. 217)
Past experience	Memories of past events
Epistemological commitments	Beliefs about how to evaluate knowledge and justification
Metaphysical beliefs and concepts	Beliefs about the general nature of the universe or science
Other knowledge	Knowledge from other disciplines, or competing understandings of the same phenomena

interpreting and combining new information to construct their own understandings. From the conceptual ecology perspective, it makes little difference to the learner if researchers consider "engineering" to be a social construct and "gravity" to be a physical phenomenon; it is the students' constructed understanding of the concept that affects learning and behavior.

Summary of Need for Study

Conceptual understanding research, as well as the current paradigm of learning theories, suggests that education efforts need to take into account students' existing beliefs about the field of engineering in order to be effective. Studies of college-level students' beliefs about engineering as a field suggest persistent misconceptions about engineering that are of key importance in career-choice and persistence decisions (National Research Council, 2008; Seymour & Hewitt, 1997). It is unclear, however, how secondary students' beliefs become or influence their beliefs during college.

Purpose and Research Questions

In order to address the purpose stated above, the following research questions will be addressed:

- How do these high school students understand the concept *engineering*?
- How might the students' conceptual ecologies of *engineering* relate to their ability to learn about it?

Methods

Research Setting

This research was performed in a small, rural high school of less than 500 students. The school draws students from a wide geographic area, and serves as the primary high school outlet for several middle schools. The town in which the school is located is on the border of a large Native American reservation. The Office of the Superintendent of Public Instruction website reported that approximately half of the students in this high school are Native American, approximately 40% are Caucasian, and approximately 4% are Hispanic. Over half of the students receive free or reduced-price lunch, indicating a community with limited financial resources. A large engineering-related industry (a power-generating facility) and tourism form the backbone of the local economy. The tribal government on the reservation is also a significant employer.

The school faces some historic challenges, including chronically low funding and below-average scores on standardized tests (around 20% passing the math and science sections of the state's standardized tests for 10th grade).

The researchers were engaged with the students at this school as part of a project intended to increase secondary students' exposure to engineering by having engineering graduate students engage with them in their classes. The researchers worked with two instructors as the school, and presented activities to their eight classes of approximately 25 students for a total of about 100 unique students. The researchers visited the school approximately twice a month for two days per visit. During these visits the researchers led the classes through lab activities designed to support their learning objectives as well as increase their familiarity with engineering. The data collection for this study was conducted during class time over three of these two-day visits.

Participant Selection

The researchers interacted with about 100 students during the course of the year. The goal of the participant selection was to obtain a reasonably representative sample of these students with a sample size of about 30. Thirty students were invited to participate in the study based on their willingness to talk to the researchers. In an attempt to include multiple perspectives, approximately half of the students chosen were interested in a career in engineering and half were not. Twenty-seven students participated in the interviews.

Note that the students sampled are not likely to be representative of a larger population of interest, but that this does not prevent the study from answering the research questions or constructing valuable findings. In the public school environment participation in a research study is strongly influenced by parental and teacher consent, student interest, and scheduling constraints. In many ways, access is the key force affecting sampling decisions (Patton, 2002). Access is about more than being able to schedule meetings with students, however, and also includes trust and open channels of communication between researcher and student. The sample chosen in this study provides unique access to a sampling of high school students with whom the researchers had developed a rapport over the course of a year of classroom visits.

Although, in many ways, this is a sample of convenience, we have applied Patton's construct of "purposeful sampling" to evaluate the rigor of our choices. Patton (2002) writes, "…in all purposeful sampling decisions, the researcher has an obligation to present the rationale and expected benefits of this strategy as well as to note its weakness (lack of generalizability)."(p. 234) Access to these students is rare and hard to come by, and therefore their involvement with this process is the expected benefit that outweighs the potential for their being a "biased" or "unrepresentative" sample. In much of his work on conceptual understanding diSessa argues that repeated interviews and rapport with participants are absolutely necessary to accurately portray the participants' ways of thinking (diSessa, 1993, 2007; Smith, diSessa, & Roschelle, 1994). As a loose measure of the rapport developed with the students, approximately 10 students spontaneously volunteered to be interviewed as a favor to the researchers. These students were interviewed using a different protocol and are not included in this study.

Interviews

Semi-structured clinical interviews (Ginsburg, 1997) were conducted by the two researchers who had been working with the students throughout the school year. The interviews were conducted over a two-day period near the end of the school year, during normal classroom activities, and lasted about 15 minutes. The interviews were audio-recorded in the classroom setting to ensure that students were able to respond in the most natural way possible, and to allow them to participate without sacrificing other commitments or time.

Clinical interviews, as described by diSessa (2007) are primarily intended "…to allow the interviewee to expose his/her 'natural' ways of thinking about the situation at hand. An assumption is that subjects' ways of thinking are delicate and complex, and skill is necessary to surface them in a mutually intelligible way" (p. 525). The interviews in this study are clinical in the sense that they are intended to bring to light the conceptions have of engineers, including the conceptions that the students may be unaware of or unable to communicate.

Semi-structured interviews allowed the interviewers to tailor each interview to the participant and to improve the interview protocol during data collection, while allowing comparison between interviews. The freedom to follow up on certain questions also made it possible to work around or clarify key vocabulary differences between the researchers and participants. For example, many students stated that engineers "fix things," but further questions about the details of "fixing" revealed that some students were using the word similar to the sense of "fixing" a game of chance to ensure a certain outcome—which is more similar to what the researchers would call design than mechanical maintenance. These interviews are semi-structured because each interview was based on the same set of standard questions, but developed differently depending on the students' responses and the interviewers' ongoing analyses.

The standard questions that guided each interview are listed below:

- What do you think of when you hear the word "engineer?"
- Do you think you could be an engineer? Why or why not?
- Why do you think some people want to be engineers?
- Please tell me about some different kinds of engineers.
- Do you know any engineers?
- Do you remember when you started thinking about engineering? Has it changed recently?
- Have you considered a career in engineering? Why or why not?
- What do you think the difference between a scientist and an engineer is?
- What do you think the difference between a construction worker and an engineer is?

These questions developed iteratively with the research questions through interaction with the participant students. Through small assessments of the researchers' frequent attempts to share facets of engineering with the students it became apparent that students' understanding of *engineering* was varied, and in nearly every case different than that of the researchers. These small assessments also highlighted the students' sensitivity to closed-ended questions that apparently have a single correct answer. For this reason, all of the standard interview questions and the extemporaneous follow-up questions were carefully worded to encourage students to explain their own experiences and ideas, rather than report their understanding of some external or presented concepts.

Clinical semi-structured interviews allowed the researchers to investigate concepts as collections of entities in an interrelated web as required by the theoretical framework guiding this research. Many students are uncertain what engineering is, and this means that students may not be able to answer direct questions about the definition of engineering and may not even think of engineering in the same context as the interviewers. Semi-structured clinical interviews framed in terms of conceptual ecology, however, provided a means to learn about students' conceptions of engineering by investigating related concepts.

Analysis

The interviews were transcribed and then analyzed qualitatively using the constant comparative method (Maykut, 1994; Miles & Huberman, 1994). The constant comparative method involves three primary steps that are repeated recursively until themes emerge. The first step is to familiarize oneself with the data. This consisted primarily of reading the transcripts and listening to the audio-recorded interviews. The second step is pattern-coding (Miles & Huberman, 1994), in which similar statements are labeled. For example, student responses to each standard interview question were labeled as a part of this step. The third step of this process is the collection and checking of themes (Braun & Clarke, 2006). Themes are groupings of pattern codes that are formed based on a theoretically important inference. For example, in this study, all of the student quotes coded under "Building," "Fixing" or "Build vs. Design" during the first two steps of analysis were grouped into a theme concerning confusion the differences between construction and engi-

Table 2
Sample of codes used in analysis.

Name of code	Description of code	Quotes	Students quoted (of 27 total)	Theme	
Building	Reference to construction or building in describing engineering	58	20	Design and Building	
Fixing	Reference to fixing or maintenance in describing engineering	32	19		19
Build vs Design	Students' descriptions of how design is different than building	27	19		
Design	Reference to design or planning in describing engineering	44	14		
Engineers In Comparisons	Descriptions of engineering dependent on comparisons	45	24		
Science	Reference to science, experiments, studying or research in describing engineering	30	13	Comparisons to Science and Math	
Math	References to math	67	21		
Where Does Math Fit?	Unrealistic examples of how math could be applied in engineering	54	23		
Help People	Definitions of engineering including helping people	5	3	Service to Society	
Working with People	References to working with various people as part of engineering	11	8	Multifaceted Engineering*	
Find Out	Definitions of engineering including seeking out information or solutions	11	10		
Creative	Definitions of engineering including creativity or generating new solutions	10	7		
Electronics	References to engineering including electronics	4	4		
Vehicles	References to vehicles (mostly cars and airplanes) in describing engineering	14	9		
Environmental	References to the environment or environmental engineering	17	11		
Confused	When students reference their confusion about engineering	12	8	Uncertainty about Engineering	

*Note that the "Multifaceted Engineering" theme is different from the other reported themes in two primary ways: 1) it is only truly applied to those students who made statements applying to multiple codes, so the number of quotes listed in the table far exceeds the number of occurrences of this theme, and 2) it draws on and therefore overlaps with many of the other codes and themes listed.

neering. Braun and Clarke (2006) describe checking themes as a process of comparing the meaning of the theme with each individual statement coded under it, and with the body of data as a whole. A vitally important part of this process is the iterative comparison of actual student statements with the successively interpreted labels being applied.

Table 2 shows some of the codes developed during this analysis, including how many statements they were applied to and how many participants those statements came from. The last column links these codes to the sections of the Results they informed. The "Uncertainty about Engineering" theme draws from all the codes listed in the table. Note that this is not a complete list, but is intended to illustrate the coding process in greater detail. Some of the codes listed were primarily generated through a first pass of pattern-coding, whereas others were generated through the process of building themes. For example the "Where Does Math Fit?" code was generated as a sub-set of the "Math" code as it was noticed that many references to math included confusion as to how it could be applied to engineering. Similarly the "Engineers in Comparisons" code arose from the development of the theme of comparison referenced in the Discussion section.

Salient and important themes were identified based on how many statements they related to in total, and on how many students made related statements. The themes reported in this paper were among the most cited, and related to more than half of the students interviewed.

Results

This section summarizes students' understandings of the concept of *engineering*, and thereby addresses the first research question guiding this research. Students' understandings will be interpreted in terms of the conceptual ecology framework in the Discussion section, which addresses the remaining research question. Note that student names have been replaced with pseudonyms.

Most students' understandings of engineering were defined by the following three features: an emphasis on designing and building; difficulty differentiating engineering from science and math; and a general uncertainty about the concept. Two additional features were important to a smaller, though still significant portion of students: (1) an emphasis on the social service inherent in engineering and (2) a complex view of engineering as a discipline with many facets. These last two features of student understanding because of their possible importance in understanding the potential of students to learn about engineering as a concept.

Design and Building

About half of the students associated engineering with "designing" or "planning" things that were to be built. For example, when asked if engineering was a part of the local power generation facility, one student answered, "Yeah.

They have to plan it all out, like the architecture. So, then they had to build it, like welding and all that stuff. People built it for them." As is typical, this student did connect engineers with planning, but also with the construction of the structure (as was made clear throughout the rest of her interview). Adrian, for example, said, "I think engineers design it and construction workers build it." This statement isn't as clear as it seems, though, because Adrian defined design as "to create," and expressed that the activity she had done in school that was most like engineering was "building that little bridge…and testing it." Again, this pattern of verbally identifying engineering with design or planning, while also associating it strongly with construction or building was very common among the students. Consider, for example, how the interviewer and participant struggle together to agree on a meaning for the key phrase, "put everything together:"

Interviewer: OK. Um, so what do you think is the difference between, like, a construction foreman and an engineer?

Student: Um, do the foremans just kind of, they just look over everything? I don't know. They're like managers at a restaurant or something, and they just kind of keep everything going?

Interviewer: So then, what does an engineer do?

Student: They, they are…they like, just put everything together, kind of.

Interviewer: OK. Can you explain that a little more?

Student: Um, they would be, like…I don't know how to…

Interviewer: So they put everything together, like what things do they…?

Student: Like, they put all the pieces together, whatever they're building or doing. I think they'd be the ones to put everything, just, whatever they're making or building or whatever.

Interviewer: So pieces, like, the actual steel chunks?

Student: Well, maybe not them doing it. But like, they would tell how to do it, kind of.

Students' use of key vocabulary further characterizes their understanding of engineering. Many students did not clearly differentiate the words "design," "build" or "fix." Some students defined "design" as "to create." For example, one student explained that the activities that the researchers had shared with the class (which were frequently referred to as "engineering activities") were just "what we've done in class," and not really engineering. The student continued,

Student: Except the parachute one.

Interviewer: That's engineering?

Student: I think because like, the way you have to design it to make it stay longer.

Interviewer: OK.

Student: And the different materials you can use.

Interviewer: OK. So how does that relate to, like, fixing things [their previous definition of engineering]?

Student: Yeah, fixing things, like, making it, like, if you put holes in it, how many strings you need.

In this particular exchange the student is emphasizing the word "design" as the quintessential engineering activity. The rest of the student's interview, however, further supports the student's implication that "design" and "fixing" are basically the same thing. This use of language is distinct from a simple lack of vocabulary, and instead suggests that the ideas themselves are not distinguished for the students. Some students clearly described "design" without using any of the troublesome words. For example, one student said, "Because it's like a puzzle. If you don't do it a certain way, it's not right. So they need to figure out what way they have to do it so it'll be right."

Many of the students who did not reference design focused instead on building or fixing. By far, the most common response to the opening question, "What comes to mind when you hear the word 'engineer'?" had to do with the mechanistic work of building or fixing. Building or fixing things was the primary component of the definition of *engineering* for 19 of the 27 students interviewed. Jack, for example, explained engineering as, "People building things, making things, like trying to fix them." When asked if he could become an engineer, Jack said, "I think I could. I live on a farm, so I have to fix a lot of engines and stuff like that."

Comparisons to Science and Math

Similar to their responses to the question asking them to distinguish between construction and engineering, about half of the students interviewed were able to explain the differences between scientists and engineering, typically by emphasizing that engineers are involved in building and construction as discussed in the previous section. Unlike the case with construction, none of these students settled on a coherent or satisfying (to themselves) distinction. The most confident of them phrased the distinction in terms of the real world and the laboratory, saying, "I think scientists are more in labs, and engineers are a more 'open-world' kind of thing. Like, they do more stuff besides inside their office and what-not," or, more tersely, "Scientists are indoors, engineers are out."

The difficulty began for some students when they were first asked to define engineering. Many students defined similar to the student who said an engineer was "somebody who studies things like biology, or, like chemicals or whatever to help things be more efficient in science." Similarly, Cory said that an engineer is "somebody who studies a lot."

A small group of students made arbitrary distinctions. Alex, for example, said, "I don't think they [engineers] are in one spot. They're around places. Scientists are in on spot and do research there, and then move. It's more gradual."

Sam focused on the popularity of the disciplines, saying, "Scientists probably get paid more. They get more fame." When the interviewer queried, "But they do similar things, pretty much?" Sam continued, "Yeah, just one gets paid more and one doesn't get much credit." These students' responses—typically offered with a shrug and a grin—are strong evidence that even though the students could not explain any clear differences, they felt strongly that there were some. Interestingly, although nearly all students associated math as a part of engineering, only one student struggled to differentiate between math and engineering.

Uncertainty about Engineering

As is likely clear from the student quotes above, the students were not certain about *engineering* or what it entailed. As an extreme example, Vicky refused to make any guesses about what engineers did. When asked how she might explain engineering to a younger sister or brother, she said, "I'd say, 'go ask Mom.'" Although Vicky's example is an extreme, she is characteristic of one sub-group of the interviewees who were hesitant to say much of anything about engineering because they felt they didn't know enough to answer the interview questions. Another group was similarly unable to make direct statements about engineering, but were more willing to try multiple methods of explaining it. One student, for example, answered most of the interview questions from the perspective that engineering might be like cooking, which was her favorite hobby.

Most often this uncertainty asserted itself as an inability to reconcile contradictory statements. As in many interviews, the students were reviewing their own answers to check for consistency, and were generally dissatisfied with perceived contradictions. Jeremy, for example, explained how he knew what engineers are by saying, "Some people came to my house. There's electricians, there's plumbers, and they fix the bolts [referring to electrical outlets] at my house." Jeremy was one of the students who had defined engineering in terms of design, so the interviewer asked, "do they [electricians and plumbers] do design?" Jeremy described evidence both supported and discounting the statement, and eventually just said, "I don't know." Similarly, Cory said that an engineer is "somebody who studies a lot," so the interviewer asked, "So, are most engineers at universities?" Cory seemed to agree with this logic, but was hesitant to counter her previous statement, saying, "Um, like universities, or else, like, some industry-related thing like [the power plant]…or like mills, or different factories or whatever." When asked how these jobs related to the previous statements that engineers "study," Cory became confused, saying,

Cory: OK, what was the question again?
Interviewer: Just, what do they study there?
Cory: What do they study?
Interviewer: At one of those industry jobs.
Cory: I don't know. It, I mean, it would depend on what they're doing. Like at a lumber mill, they probably study what kinds of wood are best for what, and how much are sold. I don't know, because that probably crosses the line between engineering and economics.

There is the possibility that the students' uncertainty was actually a profound lack of interest or motivation. This possibility is supported, in some cases, by the researcher's previous interactions with the students. Although the students were generally willing to engage in class-wide or small-group discussions and completed lab activities, on average less than half of them would fill out and return the two-page lab handouts. Saying, "I don't know," is often an easier response than reflecting on one's knowledge and trying to communicate. The implications of this counter-explanation will be addressed in the Discussion section.

Service to Society

Three students, Jane and Kristine believed that helping society was an important part of engineering. Jane defined engineering as "…people who help build things to make our lives easier," and when asked why some people might want to become engineers, she said, "they want to make the world a safer place [Interviewer asks 'anything else you can think of?']…to help out people who need help, and just to do what they like to do." Similarly, Kristine said, "as a job, like to earn money and stuff…and to, I don't know, to help people." Cory, in particular, referred to engineers "making life better" throughout her interview. When asked if engineers invent things, she said, "…they can invent things that will help everyday tasks go better or easier, and make things more ecosystem-friendly or whatever."

Multifaceted Engineering

Finally, two students had much more developed and precise definitions of *engineering*. Hank, for example, consistently formulated his answers in the context of design. He said that engineers "…design things like buildings and cars," and when asked to clarify, he said that they "…work with people to figure out what they'll look like." He clarified the difference between scientists and engineers by saying that they both might "study chemicals and stuff like that… but I don't think scientists build things and help people build things."

As a group, the students developed a fairly well rounded idea of engineering, including a range of sub-disciplines (i.e. electrical, environmental, civil, and mechanical) and various tasks including working with and helping people (as shown in Table 2). What is interesting, however, is how rarely any individual student invoked more than one of these defining features of *engineering*. The two students cited above stand out as the only participants whose understanding of *engineering* included a description of it as a diverse, varied, or multi-faceted concept.

Discussion

The theoretical framework of conceptual change allows the students' understanding of engineering to be interpreted in ways that can be informative about their likelihood and opportunities to learn more about engineering. Characterizing the students' understanding of *engineering* as a conceptual ecology suggests the ways in which it may be resistant to change. Strike and Posner (Posner et al., 1982; Strike & Posner, 1985, 1992) argue that conceptual change (the process of changing one's conceptual understanding of a topic) is controlled by what they call its "conceptual status" and motivation. A concept's status is a description of the role it plays in an individual's conceptual ecology of related topics. A concept's status is determined by its intelligibility, plausibility, fruitfulness (in terms of future research or problem solving) (Hennessey, 2003). When motivated, students will change from conceptions that are less intelligible, plausible, and fruitful to those that are more so.

In terms of Strike and Posner's framework, we could say that the students do not have a strong individual concept of what engineering is and therefore rely on analogies to similar fields. This makes sense, as there are very few strong exemplars of engineers in popular culture (Mina, Omidvar, Gerdes, & Kemmet, 2008) and engineering educators themselves tend to rely on similar reference points (Custer et al., 2010; Pirtle, Davis, Vaughn Koen, Mitcham, & Vesilind, 2010). Students attempt to define engineering in terms of how it is similar to science and construction, and therefore have difficulty in distinguishing it from those analogous fields. This lack of a strong central concept means that related knowledge and concepts exert a strong influence on students' understandings of *engineering* (Strike & Posner, 1992). Elaboration on this description suggests implications for efforts to educate students about engineering.

Related Knowledge

In the discussions comparing scientists to engineers, all students were asked if they thought math was an important part of *engineering*. Although the majority of students (20 of the 27 interviewed) said "yes," only a few students could provide examples. The few examples that were provided were limited to the concepts of measurements and simple geometry. Hank, for example, said that bridge engineers need to know "how far apart" to put the steel pieces, and Holly said that engineers use math in the power plant to know which pieces of equipment will fit in which rooms. Students who focused on engineers as fixers had an even harder time justifying math's importance to engineering. Jack was the only student with an example: "You need the right wrenches, the right other stuff. There's a lot of math in it, I think." All of these examples associate math with numbers, but not with operations or problem-solving. The case of Jack, a junior, is particularly interesting because he was interested in engineering as a career largely because he liked math as a subject in school. This shows that even when students are personally engaged and interested in the role of math in engineering, their knowledge of math was insufficient to support their beliefs. This is an example of how what Strike and Posner would call "related knowledge" can affect the status of a concept.

Intelligibility and Plausibility of Education about Engineering as a Concept

Judging by students' existing understandings of *engineering,* they may find the conception promoted by experts to be unintelligible. Despite obvious gaps in their familiarity with engineers and engineering, most participants in the study maintained strong associations (e.g. with construction or with scientists). Education attempts concerning engineering would likely focus on a range of engineering disciplines, and therefore might be incompatible with the students' existing perceptions of the field. Only two of the students interviewed stated or implied that there are multiple types of engineering: most tried (unsuccessfully) to reconcile their contradictory beliefs about what engineers did without differentiating between different types of engineers. Recall, for example, the case of Jeremy who could not reconcile his personal experiences of engineers and plumbers and electricians with his beliefs that they designed new things. This suggests that students may not be able to reconcile the statements that engineers are involved with environmental protection and remediation, as well as involved with projects typically associated with negative environmental impacts, such as housing developments, highways, and parking lots. In other words, the participants seemed to prefer an "either/or" definition of *engineering* as it related to similar fields, and may find more expansive and inclusive definitions unintelligible. Additionally, the "related knowledge" in science and mathematics required to understand the differences between engineering fields may be lacking, and would further reduce the intelligibility of such presentations.

There are two primary ways in which expert conceptions of engineering might be implausible to the students interviewed. First, as discussed above, the students do not have sufficient familiarity with the potential uses of math to be able to picture how it could plausibly be used to solve important problems in the world. Recall also that students strongly associated the word design with a guess-and-check approach to actually building things, and equally strongly associated "design" with engineering. There is little place in this model for the application of the fundamental, abstracted math and science they are most familiar with. Other students strongly associated *engineering* with an image of academic science, and for these students the hands-on, creative, and social aspects of the field (likely to be touted in efforts to interest students in engineering) would seem implausible. This suggests that no single conception (or misconception) of *engineering* would control the impact of education and recruitment attempts, but that a combination of factors would limit their impact on the population of students as a group.

Finally, students may not be sufficiently motivated to undergo any kind of conceptual change. As explained above, students' uncertainty may have in fact been evidence of their lack of motivation to think about their answers to the interview questions. With this level of motivation, it is highly unlikely that students would change their understanding of engineering, especially to a new conception that seemed lacking in intelligibility and plausibility.

Relation to Previous Findings

The tendency of students to define engineering as "building" matches Chacra's (2008) research with college freshmen in engineering programs, as well as findings from the Academic Pathways Study of the Center for the Advancement of Engineering Education (Atman, Kilgore, & McKenna, 2008). The diversity, even in the small sample of students involved in this study, is unexpected, however. Although not as overwhelming as the 90% of women and minorities that cited similar concerns in Seymour and Hewitt's (1997) study, it should be noted that the only participants in this study who cited "helping people" as a part of *engineering* were women. Jocuns et al. (2008) found that engineering students often enter engineering with a romantic image that includes opportunities to help people (altruism). Students choosing science, mathematics, and engineering (SME) majors commonly cite intrinsic interest and altruism as reasons for entering these fields (Seymour & Hewitt, 1997). This makes it particularly surprising that the only students in this study to include altruism as a reason for entering the field were not interested in engineering as a career.

Although the students' conceptions of engineering do not often match the version promoted by the National Academies or efforts intended to increase recruitment of students into engineering programs, it is worth considering how they might match engineering faculty's more informal descriptions of engineering. Pawley (2009) discusses the ways engineering faculty define the discipline of engineering, and finds three particular narratives that closely align with the themes of this paper: "…that engineering is about *applied science and math, solving problems*, and *making things*" (p. 310). These narrative themes are very similar to the students' tendencies to describe engineering in terms of building and through comparisons to math and science. The similarities between the students' ostensibly "immature" or "incomplete" understandings of engineering and the narratives expressed by university faculty suggest that all such definitions of *engineering* need to be more rigorously examined in the contexts of the roles they play for the individuals expressing them.

Pawley's use of the term "narratives" to characterize faculty's descriptions of engineering suggests a productive new direction for future research in this area. She writes that narratives are "literally the stories engineering educators tell, and we tell them to ourselves as much as others to make sense of our own experiences of the broader profession of engineering" (2009, p. 317). In other words, future work could consider the students' descriptions of engineering in terms of the ways they "make sense" of their experiences and identities. The questions then turn to identifying the circumstances or purposes from which these narratives grow. Future investigations could ask *why* students are conceptualizing engineering (i.e., how is their description helping them "make sense" of their experiences), as well as *how* they are doing so. Recall that conceptual change is encouraged when new conceptions appear fruitful—meaning likely to help the changee accomplish his or her goals. An important refinement of the construct of fruitfulness would be to include the purposes an individual might have in terms of defining his or her own identity. These goals may include the identity-building, discipline-defining discursive goals highlighted in Pawley's study of narratives, and research will be necessary to determine how they are encouraged or impeded by students' conceptualizations of *engineering*.

Conclusions

The students in this study could not be said to deeply understand *engineering*. As suggested in the Discussion, this may be because *engineering* is an inherently complex and multi-faceted concept that defies standardized classification. Although students do not know much about *engineering*, and appear to be aware of this lack of knowledge, this should not lead to the assumption that it will therefore be easy to educate them about it. Students' understanding of *engineering* closely interacts with their understandings of mathematics, construction, science and their personal experiences with their local power generation facility. Efforts to change the ways students think about engineering may necessitate small but important changes in the ways they think about all those related topics. The subtext of this study is that many of the students interviewed had been involved in two years of federally funded attempts to educate them about engineering as a career, with a strong emphasis on environmental engineering (owing to the specializations of the graduate students working with them). Despite these efforts, however, environmental engineering was only referenced by 4 of 17 interview subjects. If future efforts continue without taking into account students' existing understanding of *engineering*, it is likely that they will meet with similarly disappointing levels of success. Furthermore, ongoing research in the field problematizes the construct of an "expert" definition of engineering (Custer et al., 2010; van de Poel, Davis, Vaughn Koen, Mitcham, & Vesilind, 2010), for example by outlining the ways in which it is socially constructed in response to a specific context (Pawley, 2009). Students' understandings are also situated in their contexts, and changing them efficiently will require a greater understanding of that context and the students' positions within it.

Future Research Directions

As with any exploratory research, the results of this study should now be applied more broadly in a larger sample study. Larger samples could use survey-based research to investigate students' associations between large-scale civil construction projects and engineering, and test whether these associations are truly stronger than other likely associations with engineering, for example with familiar electronic or mechanical systems. Additionally, such large-scale surveys could be used to further investigate the potential connections for secondary students between interest in engineering as a career and a robust, multi-faceted understanding of engineering as a concept. Studies with larger, diverse samples could also explore potential linkages between the demographics of this sample and the national interest in increasing access of under-represented populations to engineering degrees. For example, what proportion of students view *engineering* as altruistic and multifaceted, but remain uninterested in it as a career? Is there a thematic or causal correlation between being relatively well informed about engineering and being uninterested in it for some students?

Further work could also be conducted as in-depth qualitative studies of students' conceptual understanding of the concept of *engineering*. Interventions aimed at educating students about engineering could be tested as to their efficacy in promoting conceptual change. Future studies could also attempt to identify misconceptions students hold about engineering. Misconceptions are deeply held beliefs that interfere with learning and are resistant to change. Their identification—possibly building off of the misleading or incorrect beliefs the students in this study expressed—would be an essential part in improving the ways in which secondary students are educated about engineering.

As a final thought, it is worth considering whether education about engineering can truly be expected to increase student interest in engineering as a career. Recent "nation-in-peril" narratives such as *Rising Above the Gathering Storm* (National Academy of Sciences, 2007) and *The World is Flat* (Friedman, 2005) have popularized the idea that the United States needs to graduate more engineers and scientists for economic and nationalistic reasons. In a parallel development, some researchers have noted that many students leaving engineering do so based on perceptions of engineering that may not accurately portray the field (Seymour & Hewitt, 1997). This has led to the assumption that educating students about engineering will likely increase their interest in it, and thereby solve an economic problem in a way that fits within the norms and ethics of education and educational research. This study, although not presenting sufficient evidence to challenge these assumptions, does however highlight the need to more explicitly reconcile the potential ethical conflict between efforts to help students equitably realize their career ambitions—whatever they may be—and efforts to increase the number of engineering graduates. In either case, knowing more about how students understand *engineering* and what it would take to change their understanding is a vital component of making progress.

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