Research on Engineering Student Knowing: Trends and Opportunities

JENNIFER TURNS
Department of Technical Communication
University of Washington

CYNTHIA J. ATMAN
Department of Industrial Engineering
University of Washington

ROBIN S. ADAMS
Center for Engineering Learning and Teaching
University of Washington

THERESA BARKER
Department of Industrial Engineering
University of Washington

ABSTRACT

What could we know about engineering student knowing? The answer to this question represents a form of scholarship of discovery in engineering education and a valuable complement to scholarship of teaching work in the field. To illustrate the state of this scholarship, we present twelve studies and analyze these studies across aspects of knowledge, level of experience, and research approach. We then use these analyses to identify trends in the existing research and opportunities for future research.

Keywords: knowing, learning, assessment

I. INTRODUCTION

In the engineering education community, we continually strive to improve the education we provide for our students. Current efforts include programs to prepare a diverse cadre of engineers, increased accountability about how effectively engineering programs prepare engineering students, and an interest in preparing engineers to function in a global community with ethical and professional responsibility. The community is responding with strategies such as emphasizing pedagogies known to be effective for diverse learners (e.g., cooperative learning), adopting new policies (e.g., the ABET outcome-based accreditation), creating new research centers devoted to engineering education issues, and other equally exciting developments. Underlying many of these efforts is a recognition and desire to be more learner-centered in our engineering education practices by ensuring that our educational practices recognize the characteristics of our learners.

This paper explores a type of fundamental research that is core to all of these efforts—research on what engineering students know about topics central to engineering. Such research represents one aspect of a scholarship of discovery for engineering education and is an important complement to the growing body of work in the scholarship of teaching [1–4]. To illustrate why and how this research is so critical, consider an analogy to the basic process of engineering. It is widely recognized that information about natural/social phenomena is valuable for design efforts that involve that phenomena. For example, Nike engineers might conduct research on the forces experienced by a foot during different types of sports (the phenomenon) to inform the design of new types of sports shoes (the design activity). Similarly, biomedical engineers would certainly want to have a detailed understanding of how the heart functions (the phenomenon) to design and develop interventions that support individuals with heart conditions (the design activity). In this vein, we can see the need for knowing what students know (the phenomena) to design educational experiences, assessments, etc. (the design activity). Thus, we should clearly be interested in research that sheds light on the phenomenon, in this case research on what engineering students know about topics central to engineering.

In this paper, we investigate the state of a scholarship of discovery on engineering student knowing. We have not aimed for a comprehensive review. Rather, we present a selective sample of papers that illustrates research on what engineering students know and then discuss themes represented by the collection of papers. We hope the information included in this paper not only illustrates this type of research, but also demonstrates the scope of research that is possible, generates ideas about specific research projects, helps to calibrate expectations about the amount of effort involved in this research, and excites engineering educators about the possibility of contributing to this growing research area.

The paper is organized as follows. Section II presents basic ideas that underlie the paper—current perspectives on what it means *to know*, thoughts on why research on knowing is valuable and how it can affect educational practice, and ideas about how researchers can approach the investigation of student knowledge. Section III and section IV describe our strategy for identifying a sample of studies on engineering student knowing, report on an analysis of these studies along three factors (aspect of knowing, level of experience, and research approach), and use the results of the analyses to speculate on future research opportunities. In section V we conclude the paper with some summary remarks.

II. BACKGROUND ON ENGINEERING STUDENT KNOWING

Ideas about what engineering students know, what aspects of knowledge are important to engineering, and how to best gain insight into that knowledge underlie much of what members of the engineering education community already do. Consider the following scenarios:

- When an educator in a dynamics class decides on the appropriate balance of concept and problem-solving questions for a test and is able to construct questions that productively discriminate among the students, this reflects a sense of some basic types of knowledge and the level of knowledge students are likely to display.
- When communication instructors bring a practicing engineer into the classroom to address an anticipated misconception (e.g., disbelief about the importance of communication in engineering), they are using an awareness of common misconceptions to make instructional choices.
- When employers and educators work together to find ways to get students' synthesis skills to match their analysis skills, this reflects a characterization of the important types of knowledge (i.e., synthesis and analysis), as well as a belief in the types of knowledge students successfully acquire and the types that need more work (i.e., they do well with analysis, but they need help with synthesis).

These scenarios form a backdrop for unpacking ideas related to knowing—ideas about what is known by whom and in what context. For example, the scenarios reflect attention to semantic knowledge, procedural knowledge, knowledge organization, and meta-cognition—key ideas in current scholarship on knowing [5, 6]. Semantic information (also, loosely, conceptual knowledge, declarative knowledge, content knowledge, knowing *what*) refers to knowledge about ideas. The complement, procedural knowledge (also skills, knowing *how*) refers to knowledge about how to do things. Semantic and procedural knowledge represent categories for describing knowledge in general. Knowledge integration and meta-cognition are important because of research on expertise. The interest in knowledge integration (a property of knowledge) reflects the finding that experts have knowledge that is organized more robustly and effectively than novices' knowledge [7]. For example, experts see connections among ideas and readily connect ideas and procedures to situations. Research on expertise has also shown that experts have an awareness of their own knowledge (and its limits) and are able to make more effective judgments of their own process (i.e., meta-cognition). For additional readings on the nature of knowing, see Svinicki [8], Martin [9], and Donovan [10].

These scenarios also reflect a sense of the specific types of knowledge that are relevant to becoming and being an engineer. For example, the scenarios allude to knowledge about dynamics, the ability to synthesize, and the role of communication in engineering. The identification of the important aspects of knowledge for engineering is not trivial and has generated much discussion. For example, the current ABET engineering learning outcomes [11], the contents of the fundamentals of engineering exam, the composition of current engineering curricula, a working definition of engineering and engineering work [12], and the results of the Engineer of 2020 project [13] all reflect ideas about what one needs to know to function as an effective engineer. Moreover, the nature of engineering knowledge has been the focus of researchers such as Vicente [14], Florman [15], and Bucciarelli [16], as well as industry-academia liaisons such as McMasters [17]. While the variety of available accounts suggests that there is no universally accepted characterization of engineering knowledge, the existing characterizations do provide powerful starting points for investigating engineering knowing.

Implicit in the scenarios is a sense not only of what is known, but also who knows it and in what context (engineering students in engineering contexts). An open question concerning research on knowing is the extent to which the results of research with one population and in one context are transferable to members of another population. In the communication and synthesis scenarios, the insights into students' knowing stem directly from experience with engineering students in engineering contexts, and thus the applicability seems apparent. To illustrate the gray area, consider the applicability of the extensive body of research on student knowledge in the domain of physics. Physics is clearly relevant to engineering, so it is likely that research on how students understand physics concepts and solve physics problems is relevant to engineering education. At the same time, because such research is often done with students working toward different degrees (e.g., medicine) and/or with problems that are not specifically within an engineering context, the transfer of these research results to engineering students and engineering problems is not well understood.

These ideas—ideas about what it means to know, what is important to know, who knows it, and in what context they know it—form the backdrop for making decisions about approaches for investigating what students know. Research on knowing involves the coupled activities of deciding what data to collect and then using the data to make inferences about what a student knows [6]. The paper by Olds and her colleagues in this issue provides a good overview of possible approaches [18]. Research approaches reflect specific ideas about the nature of the knowledge under investigation and about the kinds of evidence necessary to support a particular chain of reasoning or assertion. For example, concept maps reflect an interest in knowledge integration, the analysis of verbal protocols reflects an interest in procedural knowledge, and ethnography reflects the recognition that what someone is able to do depends on the context in which they are situated and the tools that are available. In contrast, surveys and interviews can be customized to focus on any of the types of knowledge described earlier (semantic knowledge, procedural knowledge, knowledge integration, and meta-cognition). The process for inferring a person's state of knowledge from the research data is central to using each approach in a rigorous way and thus ensuring the validity of results. Triangulation, the process of supporting claims based on data stemming from multiple sources, represents another important strategy for ensuring the validity of results [6, 19]. When, as in our case, understanding is the goal of investigating student knowledge (as opposed to student placement, grading, and program evaluation), approaches that may be too time consuming or resource intensive for other purposes may become a good choice for developing robust and rich insights into knowing.

In the context of this paper, we focus on research in which the goal is to generate robust, valid, and informative descriptions of what students know. The product of such research becomes information engineering educators can use to accomplish the types of goals implicit in the scenarios just mentioned: anticipating student difficulties, defining classroom assessments, designing and choosing among possible instructional strategies, setting realistic benchmarks, and allocating resources. When we think about these ideas for a while, we may wonder how we could possibly get engineering education to be effective without information about students' initial and progressive knowledge states? This paper speaks to this question by describing existing studies that provide information on engineering student knowing and identifying opportunities for future studies.

III. DEFINING THE SCOPE AND INTENTION OF THE SAMPLE

In selecting studies for our sample, we sought to cover three factors highlighted in the previous section: aspect of knowing, population, and research approach. Our primary focus is on what engineering students know in one or more topic areas. We want to represent studies addressing the generalized aspects of knowledge mentioned previously: semantic knowledge, procedural knowledge, and knowledge integration. We also sought to include studies focused on a range of engineering-relevant topics.

In terms of population, we sought studies that reflect what engineering students know, particularly undergraduate students, as they move through the four years of undergraduate curriculum. Also, because the applicability of research conducted with populations other than engineering students and in contexts other than engineering is an open question, we decided to take a conservative position in this paper and focus on research involving engineering students exclusively.

In terms of research approach, we sought broad coverage. In particular, we strove to identify studies that used qualitative and quantitative data, both general and more focused approaches (e.g., surveys and multidimensional scaling), and traditional techniques (e.g., interviews), as well as recent innovations (e.g., portfolio assessment). We paid attention to the rigor of the studies on several levels. For example, we looked for studies in which the work seemed to adhere to best practices for the specific method and the research approach seemed consistent with the research questions. We also looked for papers that use triangulation as a means to enhance the rigor of results.

With these considerations in mind, we assembled a sample of studies. To find potential studies, we explored the main journals and conferences in engineering education and searched engineering databases for studies on engineering-specific topics (e.g., design) and student populations (e.g., freshman). We asked colleagues to identify papers and reflect on current efforts in the field. Our final step was to review the core of possible studies we identified and select those that serve the purposes of this paper.

The twelve studies ultimately selected are characterized in Table 1 and are described more fully in the Appendix.

As Table 1 shows, the studies speak to various aspects of knowledge across populations with varied levels of experience and use varied approaches for investigating that knowledge. The papers also came from multiple sources and were written for multiple purposes. Collectively, the papers represent five journals (*Chemical Engineering Education, Design Studies, Journal of Engineering Education, Journal of Science Education, and Research in Engineering Design*) and three annual conferences (American Education Research Association, American Society of Engineering Education, and Frontiers in Education). In terms of purpose, four of the papers focus primarily on presenting data on engineering student knowing [21, 23, 28, 29]. Among the other papers, three focus on describing an assessment method [22, 25, 30], while four focus on instructional experiences [20, 26, 27, 29]. The remaining paper focuses on creating a tool to address the engineering education community's challenge of predicting retention among engineering students [24].

In the next section, we focus on what the sample of studies can tell us about the state of research on engineering student knowing. Central to our analysis is the idea that the three factors underlying our choice of the studies can be used to define two-dimensional spaces (e.g., aspect of knowledge by research approach) and even a three-dimensional space (i.e., aspect of knowledge by population experience level by research approach) in which one can locate each of the studies. Creating such representations of the studies enables various audiences to see patterns and identify opportunities for future work.

IV. DEVELOPING A LANDSCAPE OF RESEARCH ON ENGINEERING STUDENT KNOWING

A. Looking at Knowledge Across Levels of Experience

Figure 1 organizes the twelve studies to highlight the experience level of the populations in the studies. In the figure, the horizontal axis represents the experience level of the populations represented in the studies. The categories represented on the axis reflect the authors' categorizations and are also presented in Table 1. The vertical axis represents the aspects of knowledge addressed in the collection of papers. These aspects of knowing are sequenced loosely from concrete to abstract and specific to general moving from the top to the bottom of the axis.

A mark at the intersection of a column (experience) and a row (aspect of knowing) indicates that at least one of our studies addresses that specific population/knowing combination. The letters next to the marks show the specific mapping back to the studies. Thus, more than one letter indicates that more than one study addressed the population/knowing combination. In most cases, the studies from Table 1 map to one row in the figure because the researchers were focusing on one key aspect of knowing. In the cases where the researchers in the studies were investigating more than one aspect of knowing (see Table 1), their studies are represented in more than one row in the figure. Because this paper was not meant to be a comprehensive review, the coverage represented by the figure underestimates the amount we know about knowing from the literature.

This type of figure makes certain observations easy to identify, specifically observations about what is there (coverage), what is not there (absence), and what trends exist (patterns). The smattering of marks across the figure reflects the variety of research uncovered. By looking across a row of the figure, one can gain a sense of the populations included in the research on a specific aspect of knowledge. For example, the figure makes it clear that our sample of studies provide insights on teamwork knowledge at only the freshman level and intellectual development at freshman, junior, senior, and alumni levels. When the research involves more than one population (as in the case of the research on design processes), the resulting information could represent a trajectory that can help us understand how students' knowledge might evolve as students move through their education. If we look at the columns in the figure, we can gain a window into student knowledge at a particular level of experience (e.g., the knowledge of freshman). For example, we can see a cluster of studies related to freshman students and a cluster related to senior students.

The collection of studies in the sample provides a starting point for a description of freshman knowing. The studies that included freshmen covered eight different aspects of knowing, ranging from the types of conceptions and misconceptions students have of the

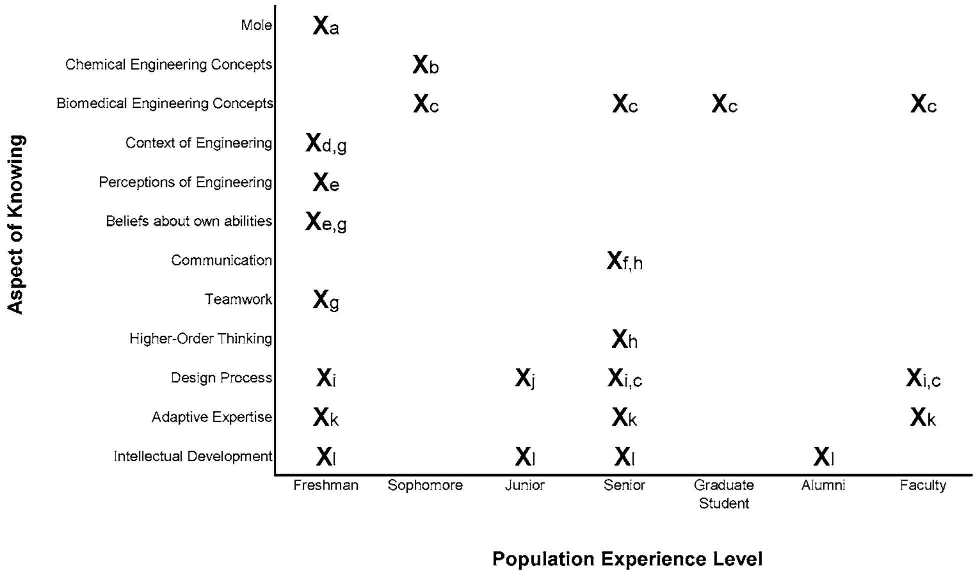


Figure 1. Characterizing studies in terms of aspect of knowing and experience level of the population. The subscripts refer to the studies that are listed in Table 1.

concept of *mole* to a characterization of the intellectual state of freshmen according to the Perry model. Through this sample and at a gross level of generalization, we see freshmen as students with some persistent misconceptions concerning the concept of mole [20], a flexibility in generating ideas related to global and social issues [23], a generally positive perception of engineering [24], a generally positive belief in their own abilities [24], some negative associations with teamwork [26] coupled with an ability to engage in a successful teamwork experience [26], a tendency to get stuck in the modeling stage of design [28], and a tendency toward a Perry position of "3-Multiplicity" in which they believe that "knowledge is right or wrong but some knowledge is unknown" and "authority is the source to find the answers" [31]. Clearly, this is a broad characterization that glosses over the variability in the studies and the individual differences of students. However, this characterization also begins to illustrate (particularly to the educator who works regularly with freshmen) what could be achieved if all the research on freshmen was synthesized and more was added.

The same exercise with seniors reveals that six studies shed light on seniors concerning six aspects of knowledge. For example, the studies revealed some aspects of engineering writing that still seemed to challenge senior-level students [25], an ability of senior-level students to reach the "latter" stages of the design process—explicit attention to comparing alternatives and making decisions [28], and an ability of senior chemical engineering students to improve the quality of the insights they present in their chemical engineering laboratory reports at the end of a summer workshop [27]. It is interesting to point out the inclusion of discipline-specific information at the senior level (e.g., biomedical engineering concepts) and the implication of the range of additional discipline-specific concepts and skills that could be added to address the collection of engineering disciplines.

The collection of studies in the sample also permits us to see where the results are starting to provide a longitudinal perspective on an aspect of knowing over time. There are at least two strategies for creating longitudinal views. A within-subjects longitudinal study results in images of the *same* student at different points in time. For example, the Walker and King study involved senior-level students creating concept maps at the beginning, middle, and end of a year of design instruction [22]. A between-subjects study design provides a more readily feasible approach to getting a longitudinal perspective: this is the approach taken in one of the design process studies reported in this paper [28]. Longitudinal study designs could also include both within- and between-subject data, such as the study on intellectual development described by Marra and her colleagues [31]. Either way, data that provide a longitudinal perspective point our attention not simply to states of knowledge but also to the possible trajectory of that knowledge over time. Imagine the powerful insights a larger set of longitudinal studies for more aspects of knowledge could afford the community.

As the above examples suggest, the representation in Figure 1 can help researchers identify what we know and decide what to study next. This representation can also be viewed by other audiences with an eye toward how they can make use of the findings to achieve their goals. Educators teaching in one or more of the knowledge areas represented by the studies can use the results to develop expectations of their students and subsequently make judicious decisions about instruction and assessment. Those exploring the alignment between academic preparation and employer needs would likely be most attracted to the collection of studies focused on seniors. The results of these studies could be shared with employers and used to elicit and/or calibrate their expectations. For example, employers could be shown the results of studies about teamwork knowledge and ability, asked if they find the levels of knowledge/skill acceptable, and asked what additional knowledge they would like engineering graduates to possess. Such a conversation may be more concrete than conversations without such rich referent data. One of the ways that policy makers could use the results is to set realistic benchmarks anchored in real abilities. For example, we might look to the most successful of our students in areas of design or content knowledge and then attempt to set a benchmark of enhancing education so that a specific percentage of students can ultimately achieve that level of success. The results can

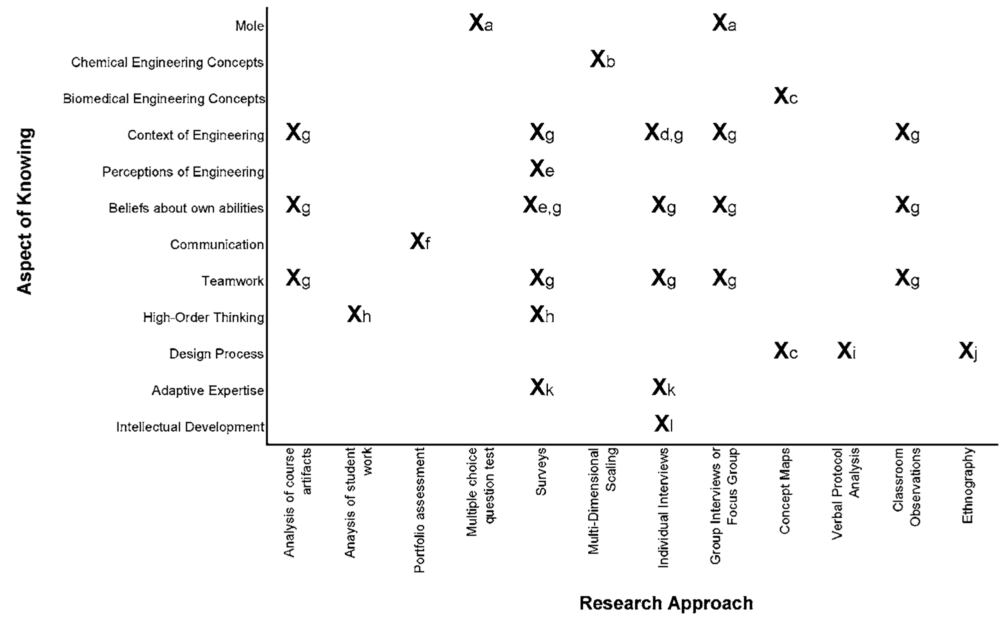
Article Title, Authors and Date	Knowing	Population: Level of Experience	Population: Discipline	Research Method or Approach
a. "An Investigation into Chemical Engineering Students' Understanding of the Mole and the Use of Concrete Activities to Promote Conceptual Change," Case & Fraser, 1999 [19]	Mole	Freshman	Chemical Engineering	Group interviews Multiple choice question test
b. "Persistent Student Misconceptions in Engineering," Streveler & Miller, 2002 [20]	Introductory chemical engineering concepts: - Conservation - Chemical processes and systems	Sophomore	Chemical Engineering	Multidimensional scaling (MDS)
c. "Concept Mapping as a Form of Student Assessment and Instruction in the Domain of Bioengineering," Walker & King, 2003 [21]	Biomedical engineering concepts Design	Sophomore, Senior, Graduate Student, Faculty	Biomedical Engineering	Concept maps (by individuals and pairs)
d. "Engineering in Context: An Empirical Study of Freshmen Students' Conceptual Frameworks," Atman & Nair, 1996 [22]	Context of engineering: - Science, technology, and society issues	Freshman	Engineering Non-Engineering	Individual interviews (structured, open-ended)
e. "Characteristics of Freshman Engineering Students: Models for Determining Student Attrition in Engineering," Besterfield-Sacre et al., 1997 [23]	Perceptions of engineering: - As a field - As an exact science - As a well paid field with career security Beliefs about own abilities	Freshman	Engineering	Surveys
f. "Outcomes Assessment of Engineering Writing at the University of Washington," Plumb and Scott, 2002 [24]	Writing	Seniors	Engineering	Portfolio assessment
g. "From the Students' Point of View: Experiences in a Freshman Engineering Design Course," Courter et al., 1998 [25]	Teamwork Context of engineering Beliefs about own abilities	Freshman	Engineering	Individual interviews (open-ended) Focus groups Observations Surveys Course artifacts
h. "Higher-Order Thinking in the Unit Operations Laboratory," Miller et al., 1998 [26]	Higher-order thinking: - Analysis - Synthesis - Evaluation Communication	Senior	Chemical engineering	Analysis of student work (laboratory reports) Surveys
i. "Educating Effective Engineering Designers: The Role of Reflective Practice," Adams et al., 2003 [27]	Design - Design processes - Iteration - Information gathering - Problem scoping	Freshman Senior	Freshman Civil, Industrial and Mechanical engineering	Verbal protocol analysis
j. "Of Green Monkeys and Failed Affordances: A Case Study of a Mechanical Engineering Design Course," Newstetter, 1998 [28]	Design	Juniors	Mechanical engineering	Ethnography
k. "A Tool to Measure Adaptive Expertise in Biomedical Engineering Students," Fisher & Peterson, 2001 [29]	Adaptive expertise	Freshman Senior Faculty	Biomedical engineering	Surveys Individual interviews
l. "Longitudinal and Cross-Sectional Study of Engineering Student Intellectual Development as Measured by the Perry Model," Marra et. al., 1998 [30]	Intellectual development (Perry Model)	Freshman Junior Senior Alumni	Engineering	Individual interviews (semi-structured)

Table 1. Studies in the sample (see Appendix for more detailed descriptions of each study).

also be viewed by those who make decisions about resource allocation. Such individuals could use the results and patterns of results (e.g., findings that are deemed unacceptable, a lack of findings that are desirable) to determine what aspects of education to prioritize.

B. Looking at Knowledge Across Research Approaches

Figure 2 organizes the studies to highlight the various research approaches. In the figure, the vertical axis represents the aspects of knowledge addressed in the collection papers. This axis is identical to the previous figure. The horizontal axis represents the approaches used in the studies. The categories listed on this axis represent the authors' characterization of their own work. Because our sample was not exhaustive, the collection of approaches does not necessarily represent the body of approaches available. The collection is broad, however, because we did seek to include a wide variety of approaches to illustrate the possibilities.



Aspect of Knowing	Analysis of course artifacts	Anaysis of student work	Portfolio assessment	Multiple choice question test	Surveys	Multi-Dimensional Scaling	Individual Interviews	Group Interviews or Focus Group	Concept Maps	Verbal Protocol Analysis	Classroom Observations	Ethnography
Mole				X_a				X_a				
Chemical Engineering Concepts						X_b						
Biomedical Engineering Concepts									X_c			
Context of Engineering	X_g				X_g		$X_{d,g}$	X_g			X_g	
Perceptions of Engineering					X_e							
Beliefs about own abilities	X_g				$X_{e,g}$		X_g	X_g			X_g	
Communication			X_f									
Teamwork	X_g				X_g		X_g	X_g			X_g	
High-Order Thinking		X_h			X_h							
Design Process									X_c	X_i		X_j
Adaptive Expertise					X_k		X_k					
Intellectual Development							X_l					

Figure 2. Characterizing studies in terms of aspect of knowing and research approach used. The subscripts refer to the studies that are listed in Table 1.

As with Figure 1, a mark at the intersection of a column (approach) and a row (aspect of knowing) in Figure 2 indicates that at least one of the studies used that specific approach/knowing combination. The letters next to the marks show the specific mapping back to the studies. Thus, more than one letter indicates that more than one study addressed the approach/knowing combination.

Looking across the rows of Figure 2, we can get a sense of the number of methods used to investigate each of the aspects of knowing represented in the sample. In some cases, the research used one approach. For example, the insights into intellectual development represented in the table stem from research using individual interviews. Using a single method has certain advantages. Since each approach has its own logic (i.e., processes, procedures, theory, standards of rigor), studies that focus on one approach may be more likely to be true to those standards. For example, both ethnography and surveys can be challenging to implement effectively. When a researcher focuses on using a single approach, there is more time to focus on the quality of the data collected using that approach. At the same time, there are also significant benefits to having information from multiple approaches available so that findings can be triangulated. Figure 2 highlights some of the instances where multiple approaches were used in the same study in order to investigate a single aspect of knowledge, such as the study by Courter and her colleagues [26]. The representation also makes clear that even in our small sample, there are aspects of knowledge that have been investigated by multiple researchers, with the researchers having collectively used more than one approach (e.g., context of engineering, belief in own abilities). The existence of multiple studies using multiple approaches highlights an opportunity for scholarship on integration work—efforts focused on synthesizing understanding across the different studies [1].

The three studies on design [22, 28, 29] illustrate a situation where different researchers used different methods to explore the same aspect of knowledge, creating an opportunity for integration. The studies use three methods (verbal protocol analysis, concept maps, and ethnography) to investigate complementary aspects of design (design process in laboratory conditions, design conceptions, and design process under situated team conditions). The paper by Adams and her colleagues [28] shows patterns in design process behavior that illustrate some of the ways students engage in problem setting. In the Walker and King work [22], the authors learned that student knowledge of the design process, as represented in concept maps, had more concepts and also more coherence after a year of senior-level design instruction. In Newstetter's study [29], she reported on the difficulty that junior-level students can have in moving between inscriptional systems involved in design work and the limited notions that students have about how to distribute design work over a design team. The composite picture that emerges reminds us of the level of accomplishment that students are actually achieving (they did create concept maps, design playgrounds, deliver on team projects), the types of knowledge involved in design, and the possible areas where students may have difficulty. This brief discussion of the three studies also illustrates the complexity of design activity (so many dimensions in just three studies) and some of the challenges associated with a scholarship of integration.

Looking across the columns of Figure 2, we can get a sense of the relative level of use of the various approaches in this sample. The representation echoes our intuition that a wide variety of approaches are in use and are being applied to issues of engineering education. A total of ten approaches are represented in our sample of studies, including surveys, concept mapping, multi-dimensional scaling, and ethnography. It is invigorating to see so many approaches being used to probe and understand engineering student knowing. The representation also echoes our intuition that some approaches may be favored by researchers in the engineering education community. For example, six of the twelve studies involved the use of surveys, something that is not surprising given that surveys are adaptable and relatively straightforward to implement and explain. The frequent use of surveys provides a good opportunity to remind ourselves to be cautious when using surveys. Surveys can be difficult to create because effective ones require a detailed understanding of the phenomena of interest.

As with Figure 1, the representation in Figure 2 can also be viewed by other audiences with an eye toward how they can use the findings to achieve their goals. Looking through the eyes of other audiences, at least two issues become relevant: envisioning tools and gauging validity. Educators, who need to find ways to assess student knowledge, may be interested in the tools used in these studies. For example, educators interested in what students are learning about the concept of mole may be interested in the knowledge test used by the researchers of that study. Of course, transforming the research-based assessments into classroom assessments may not be straightforward. For audiences working on situations that reach beyond individual educators and classrooms and involve larger-scale impacts (e.g., understanding retention issues, setting educational benchmarks), the people in the audience may be particularly concerned about the validity of the results before they may be willing to base their decisions on the results. As such, these audiences may be particularly interested in the breadth of methods used to inform the results since multiple methods provide opportunities to triangulate research results.

C. Opportunities for Future Research

These examples of the research and the utility of the research for different audiences give rise to a number of opportunities for additional studies. For example, a basic opportunity is to more densely populate the spaces defined in Figure 1 and Figure 2. In the context of Figure 1, this would consist of using the existing research design with additional populations. Such data would give us a better sense about what these aspects of knowledge look like over time so the community could get a sense of learning trajectories on these aspects of knowing. Another opportunity is to conduct studies that use other approaches that provide direct investigation into the aspects of knowledge already listed in Figure 2. For example, researchers could explore teamwork with concept maps or use portfolios to investigate design ability. Such research could be particularly valuable to those who are interested in the robustness of the results.

If we consider expanding beyond the space defined by the current studies, we see additional opportunities. For example, we could further subdivide the populations and then repeat the studies with students in these new populations. Such research could include collecting information about students at the beginning and the end of an academic year, an academic term, a complete educational experience, and even at specific points during an academic experience. We could also repeat the studies with students from underrepresented populations or students from a particular university campus or particular region. We might additionally expand the landscape by conducting studies on aspects of knowing not yet represented. For example, we could conduct studies on each of the dimensions identified by ABET [11], on the Engineer of 2020 project [13], or more specifically on the concepts and skills associated with specific disciplinary classes (e.g., circuit design, aerospace manufacturing, thermodynamics). Both of these opportunities would increase the likelihood that the research results apply to the populations with which educators work, and thus would increase the likelihood that engineering educators could make use of the research to inform teaching of their topics. Finally, we could also expand the space by exploring aspects of knowledge using approaches that are not mentioned in this representation (e.g., conversation analysis, microgenetic analysis).

Additional opportunities go beyond creating more studies and reflect ways to ensure that research impacts practice. Here, communication of applicability to practice and rigor are key. For example, we might consider exploring ways to standardize reporting of results within the community and even how we talk about research approaches, so that the results are understood more readily by readers. Two important aspects of being rigorous are being consistent with the standards associated with individual methods and being systematic in an overall approach. As such, we can also seek strategies to ensure that researchers fully describe their methodology so readers can accurately gauge the credibility of the results.

If we treat the representation in the figures as main building blocks and view them from the perspective of a tool, one opportunity would be to work with educators to understand how they might use such representations to navigate through the studies that are relevant to them and thus how to improve the representation (i.e., perhaps the cells in the figure could incorporate small graphics encapsulating some of the results). Moreover, we might imagine creating representations customized to specific interests—such as a collection of studies related to bioengineering or a collection of studies relevant for understanding retention issues.

Finally, as a community, we can recognize the important scholarship of integration piece in which researchers devote themselves to aggregating data and findings from multiple approaches/studies to create theories about engineering student knowing. Returning to Figure 1 and Figure 2, we can see that we need at least two types of integration—integration that synthesizes findings across research approaches and integration that synthesizes findings across populations. Clearly, a wide variety of opportunities exist, thus providing an opportunity for the community to come together to discuss how we might sequence such activities.

V. CONCLUDING REMARKS

In this paper, we have focused on a scholarship of discovery in engineering education that focuses on what engineering students *know*. To illustrate the state of this scholarship, we presented twelve studies and analyzed these studies across aspects of knowledge, level of experience of the population, and research approach. We then used these analyses to identify trends in the existing research and opportunities for future work.

We have not meant to suggest that this type of research is the only scholarship of discovery relevant to engineering education. For example, research on the design of effective learning environments, effective pedagogies, and the mechanisms behind retention are also basic forms of research that are of value to the engineering education community. However, we are suggesting that research on engineering knowing is an important element and something the community needs to advance. In fact, when we look to other disciplines to see how much these communities know about what students know, we find something of a link between the amount that seems to be known and the level of innovation going on in the educational practices (e.g., physics education). Moreover, the idea of expanding what we know about student knowing is echoed in the conclusion of the recent report *Knowing What Students Know*:

> "One priority for research is the development of cognitive models of learning for areas of the school curriculum. … researchers have developed sophisticated models of student cognition in various areas of the curriculum, such as algebra and physics. However, an understanding of how people learn remains limited for many other areas. Moreover, even in subject domains for which characteristics of expertise have been identified, a detailed understanding of patterns of growth that would enable one to identify landmarks on the way to competence is often lacking. Such landmarks are essential for effective assessment design and implementation" [6, p. 300].

As we think about the research opportunities identified, we realize that identifying opportunities is not enough. Even with a body of research available and representations that can help to organize the work, there will still be the research-to-practice issue of how to motivate educators to engage with the research results [32]. We hope, however, that the information presented here can address some of the possible challenges. For example, we have provided illustrations of how various audiences could use information about knowing and included examples of individual studies to inspire potential researchers about how to conduct such research. We also hope that the ideas represented in this paper can help aspiring researchers communicate their ideas and make their case for funding. Inspiring and enabling new researchers may be particularly relevant since what we are describing is not the work of individual researchers, but rather an opportunity for the community to come together and build a base of this type of research.

Conversations represent an important next step—conversations about the strength of the ideas in this paper, the relative priorities of the proposed opportunities, and the challenges yet to come.

ACKNOWLEDGMENTS

We want to thank the guest editors for their guidance as well as the reviewers of an earlier version of this paper for their feedback. We also want to personally thank Sheri Sheppard, Natalie Quilter, Jessica Yellin, Ruth Streveler, Barbara Olds, Karl Smith, and Angela Linse. Funding for this work was provided by National Science Foundation Grant ESI-0227558, National Science Foundation Grant ROLE-0125547, National Science Foundation Grant CAREER-0238392, and the Center for Engineering Learning and Teaching at the University of Washington.

REFERENCES

[1] Boyer, E.L., *Scholarship Reconsidered: Priorities of the Professoriate*, Princeton, N.J.: Jossey-Bass, 1990.

[2] Wankat, P., "An Analysis of the Articles in the Journal of Engineering Education," *Journal of Engineering Education*, Vol. 88, No. 1, 1999, pp. 37-42.

[3] Wankat, P., "Analysis of the First Ten Years of the Journal of Engineering Education," *Journal of Engineering Education*, Vol. 93, No. 1, 2004, pp. 13–21.

[4] Whitin, K., and Sheppard, S., "Taking Stock: An Analysis of the Publishing Record as Represented by the *Journal of Engineering Education*," *Journal of Engineering Education*, Vol. 93, No. 1, 2004, pp. 5–12.

[5] Bransford, J.D., Brown, A.L., and Cocking, R.R., (Eds.), *How People Learn: Brain, Mind, Experience, and School*, Washington, D.C.: National Academy Press, 1999.

[6] Pellegrino, J.W., Chudowsky, N., and Glazer, R., *Knowing What Students Know: The Science and Design of Educational Assessment*, Washington D.C.: National Academy Press, 2001.

[7] Chi, M.T.H., Glaser, R., and Farr, M.J., *The Nature of Expertise*, Hillsdale, N.J.: Lawrence Erlbaum Associates, 1988.

[8] Svinicki, M.D., *Learning and Motivation in the Postsecondary Classroom*, Williston, Ver.: Anker Publishing, 2004.

[9] Martin, L., Nelson, K., and Tobach, E., *Sociocultural Psychology: Theory and Practice of Doing and Knowing*, Cambridge, Mass.: Cambridge University Press, 1996.

[10] Donovan, M., Bransford, J., and Pellegrino, J., (Eds.), *How People Learn: Bridging Research and Practice*, Washington, D.C.: National Academy Press, 1999.

[11] Engineering Accreditation Commission, *http://www.abet.org/accreditation.html.*

[12] Sheppard, S., "Engineering Education in the New Century," Briefing document prepared for NAE Summit on the Engineer of 2020, Washington, D.C., July 22–23, 2004.

[13] National Academy of Engineering, *The Engineer of 2020: Visions of Engineering in the New Century*, Washington, D.C.: National Academies Press, 2004.

[14] Vincenti, W., *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*, Baltimore, Md.: John Hopkins University Press, 1990.

[15] Florman, S.L., *Existential Pleasures of Engineering*, New York, N.Y.: St. Martin's Press, 1994.

[16] Bucciarelli, L.L., *Designing Engineers*, Cambridge, Mass.: The MIT Press, 1994.

[17] McMasters, J.H., "Influencing Engineering Education and One Aerospace Industry Perspective," *Proceedings, Fourth Harvey Mudd Design Workshop*, Claremont, Cal., 2003.

[18] Olds, B.M., Moskal, B.M., and Miller, R.L., "Assessment in Engineering Education: Evolution, Approaches, and Future Collaborations," *Journal of Engineering Education*, Vol. 94, No. 1, 2005, pp. 13–25.

[19] Adams, R.S., Atman, C.J., Nakamura, R., Kalonji, G., and Denton, D., "Assessment of an International Freshmen Research and Design Experience: A Triangulation Study," *International Journal of Engineering Education*, Vol. 18, No. 2, 2001, pp. 180–192.

[20] Case, J.M., and Fraser, D.M., "An Investigation into Chemical Engineering Students' Understanding of the Mole and the Use of Concrete Activities to Promote Conceptual Change," *International Journal of Science Education*, Vol. 21, No. 12, 1999, pp. 1237–1249.

[21] Streveler, R., and Miller, R., "Persistent Student Misconceptions in Engineering," *Proceedings, Annual Conference of the American Educational Research Association*, New Orleans, La.: AERA, 2002.

[22] Walker, J., and King, P., "Concept Mapping as a Form of Student Assessment and Instruction in the Domain of Bioengineering," *Journal of Engineering Education*, Vol. 92, No. 2, 2003, pp. 167–178.

[23] Atman, C.J., and Nair, I., "Engineering in Context: An Empirical Study of Freshman Student's Conceptual Frameworks," *Journal of Engineering Education*, Vol. 85, No. 4, 1996, pp. 317–326.

[24] Besterfeld–Sacre, M., Atman, C.J., and. Shuman, L., "Characteristics of Freshman Engineering Students: Models for Determining Student Attrition in Engineering," *Journal of Engineering Education*, Vol. 86, No. 2, 1997, pp. 139–149.

[25] Plumb, C., and Scott, C., "Outcomes Assessment of Engineering Writing at the University of Washington," *Journal of Engineering Education*, Vol. 91, No. 3, 2002, pp. 333–338.

[26] Courter, S., Millar, S., and Lyons, J., "From the Students' Point of View: Experiences in a Freshman Engineering Design Course," *Journal of Engineering Education*, Vol. 87, No. 3, 1998, pp. 283–287.

[27] Miller, R.L., Ely, J.F., Baldwin, R.M., and Olds, B.M., "Higher-Order Thinking in the Unit Operations Laboratory," *Chemical Engineering Education*, Vol. 32, No. 2, 1998, pp. 146–151.

[28] Adams, R.S., Turns, J., and Atman, C.J., "Educating Effective Engineering Designers: The Role of Reflective Practice," *Design Studies*, Vol. 24, No. 3, 2003, pp. 275–294.

[29] Newstetter, W.C., "Of Green Monkeys and Failed Affordances: A Case Study of a Mechanical Engineering Design Course," *Research in Engineering Design*, Vol. 10, No. 2, pp. 118–128.

[30] Fisher, F.T., and Peterson, P.L., "A Tool to Measure Adaptive Expertise in Biomedical Engineering Students," *Proceedings, 2001 American Society of Engineering Education Annual Conference*, ASEE.

[31] Marra, R., Palmer, B., and Litzinger, T., "Longitudinal and Cross-Sectional Study of Engineering Student Intellectual Development as Measured by the Perry Model," *Proceedings, 1998 American Society of Engineering Education Annual Conference*, ASEE.

[32] Turns, J., Adams, R.S., Linse, A., and Atman, C.J., "Bridging from Research to Practice in Undergraduate Engineering Design Education," *International Journal of Engineering Education*, Vol. 20, No. 3, pp. 379–390.

[33] Atman, C.J., and Turns, J., "Studying Engineering Design Learning: Four Verbal Protocol Studies," in *Knowing and Learning to Design: Cognitive Perspectives in Design Education*, C. Eastman, M. McCracken, and W. Newstetter (Eds.), New York, N.Y.: Elsevier, pp. 37–62, 2001.

[34] Atman, C.J., Chimka, J.R., Bursic, K.M., and Nachtmann, H.L., "A Comparison of Freshman and Senior Engineering Design Processes," Design Studies, Vol. 20, No. 2, 1999, pp. 131– 152.

[35] Adams, R.S., "Understanding Design Iteration: Representations from an Empirical Study," *Proceedings, International Conference of the Design Research Society*, London: DRS, 2000.

[36] Bursic, K.M., and Atman, C.J., "Information Gathering: A Critical Step for Quality in the Design Process," *Quality Management Journal*, Vol. 4, No. 4, 1997, pp. 60–75.

APPENDIX

This appendix contains descriptions of the twelve studies included in this paper and listed in Table 1. In describing the studies, we have endeavoured to stay true to the ideas of the authors by using their terms and, in many cases, using quotes from the authors to capture the results of the study. The letters associated with each study provide a means of cross referencing the studies in Table 1, Figure 1, and Figure 2.

1) An investigation into chemical engineering students' understanding of the mole and the use of concrete activities to promote conceptual change (Case and Fraser [20]): This study investigated student misconceptions about the concept of "mole," a central concept in chemical engineering. The research proceeded in two phases. In the first phase, fifteen freshman were interviewed to investigate chemical engineering students' understandings of the mole concept, using an interview protocol that built on previous research into student difficulties with this concept. Analysis of the interviews suggested the presence of three distinct misconceptions: "A. The amounts of kmol, lbmol, and gmol are seen as masses," "B. The amounts of kmol, lbmol, and gmol are all the same, because they are all a mole," and "C. The volume of a gas is not seen as proportional to its amount" [20, pp. 1240–1241].

In the second phase, the researchers developed a conceptually oriented multiple choice test targeting the three misconceptions. They then used the test to learn more about the initial conceptions of their first-year chemical engineering students (via a pre-test) and to understand the impact of an intervention designed to address the misconceptions (via a post-test). When the multiple choice test was used as a pre-test with eighty-one first-year chemical engineering students, the researchers found the following:

"More than one-third of the students seemed to hold misconception A (moles seen as masses)…

"Evidence for misconception B (gmol, kmol and lbmol are the same) can be seen in the scores … approximately one quarter of the sample demonstrated misconception B…

"Evidence for misconception C (difficulties with proportionality of amount and volume) is displayed in the results … with a similar percentage of the sample displaying this misconception as misconception B" [20, pp. 1242, 1243].

After the intervention, which is described in more detail in the paper, the researchers found slight improvement relative to misconceptions A and B but little evidence of change with respect to misconception C.

2) Persistent student misconceptions in engineering (Streveler and Miller [21]): This research focused on student conceptions of conservation concepts in the context of chemical processes and systems. Twenty chemical engineering students (sophomores) were asked to sort thirty-one conservation concepts, such as conservation of mass and conservation of energy, into logical groupings. Data from the grouping exercise were used to create a class-level similarity matrix, which was then transformed via multidimensional scaling (MDS) into a single knowledge map showing the students' collective understanding of the relationships among the concepts. The researchers completed this sequence of events twice, once prior to instruction and again following instruction.

To analyze the two knowledge maps, the researchers attended to concepts that did not seem to belong to any grouping (i.e., were not physically close to any other concepts), suggesting that students were having difficulty understanding the concept in relation to other concepts. They also used the clustering of the concepts in the maps (via the physical proximity of concepts) to characterize the way students seemed to understand the relationships among the chemical engineering concepts, and then had a subject matter expert in chemical engineering comment on the appropriateness of these relationships. The researchers noted that two terms went from being clustered in the pre-test to unclustered in the post-test (equilibrium constant, process flow diagram), suggesting either increased confusion about the concepts or increased awareness of a lack of true understanding of the concepts. The researchers found seven concept clusters in both the pre-test and post-test, but noted that the nature of the clusters changed. For example, one of the post-test clusters was the combination of two pre-test clusters in which all concepts were related to energy issues, suggesting a growing understanding of the underlying function of the concepts. One of the more significant results related to the concept of work. In the words of the researchers:

"However, this [cluster] group should also contain the term *work*, which in both the pre-test and post-test remains separated from any group. Energy flowing as heat can also be converted to mechanical work and thus, heat, work, and energy are related, but not equivalent terms. Thus heat terms, energy terms, and work should be grouped together by students …. Why is the concept of *work* so persistently misunderstood, while other possible misconceptions seem to have been repaired with instruction? And how can instruction be designed to assist students in correcting this misconception? Since mechanical work is defined as force times distance, we speculate that misconceptions about the concept of *work* may be tied to misconceptions about *force*" [21, p. 6].

3) Concept mapping as a form of student assessment and instruction in the domain of bioengineering (Walker and King [22]): This paper reports on two studies investigating concept mapping as a form of student assessment within biomedical engineering. In each study, participants were asked to identify important concepts related to a topic and spatially arrange the concepts to demonstrate relationships between them. Analysis of a concept map builds on the idea that the concepts and linkages between concepts in the map are a reflection of the breadth and level of integration of the knowledge of the person(s) who constructed the map.

In the first study reported in the paper, four sophomore-level undergraduate biomedical students, four senior-level undergraduate biomedical students, nine doctoral students, and three faculty members (all volunteers) were asked to construct concept maps by identifying the ten to twenty most important concepts in biomedical engineering (BME) and then building the map from the terms. Analysis of the results showed no quantitative differences among groups (in terms of number of concepts, number of links, concept:link ratios), but did show qualitative differences:

"With regard to qualitative differences, faculty maps contained higher-order principles (e.g., 'the synthesis of engineering and medicine') and their applications (e.g., 'communication with professionals outside the field'). By contrast, students generated fewer connections among concepts pertaining largely to domain content (e.g., 'biotechnology,' 'physiology'). While faculty also mentioned domain knowledge, their maps highlighted important core competencies or the application of domain knowledge (e.g., 'persuasiveness,' 'understanding the context of technology in health care'). References to these competencies were rare among student maps, even at the graduate level. Fundamentally, this difference suggests that students either do not consider, or do not know how to consider, themselves members of a community of practice. However, because there was a great deal of variability among the expert maps, systematic comparison of student maps to an 'expert' criterion map was largely impossible" [22, p. 169].

In the second study, four senior biomedical students and the instructor were asked three times during the academic year: "What is your current conceptual understanding of what is involved in the BME design process?" The four students worked in pairs to construct concept maps in response to the question. In the researchers' words, "Analyses showed important quantitative and qualitative differences between each pair's initial and later maps: later maps contained more concepts, greater precision in vocabulary, and were more coherently constructed" [22, p. 171]. For example, the maps grew from fourteen to twenty-six concepts for the first pair, and from twenty-seven to fifty-five concepts for the second pair. By evaluating the maps with a rubric for gauging validity, the researchers found that the validity score of the maps went from seventeen to forty-six for the first pair and from fifty-four to 124 for the second pair. The researchers also reported a number of qualitative observations within and across the pairs, such as a shift from a hierarchical to a network representation by pair one and a greater emphasis by pair two on the needs of the client and legal issues. Because the paper includes many examples of the concepts maps from both studies, it is possible for readers to investigate the maps further on their own.

4)Engineering in context: An empirical study of freshmen students' conceptual frameworks (Atman and Nair [23]): In this study, the researchers investigated freshman students' conceptions of the context of engineering, specifically science, technology and society issues, and possible differences between the conceptions of engineering and non-engineering students. The researchers used structured, open-ended interviews with ninety-two freshman students (half engineering, half non-engineering) to elicit student knowledge about two topics: "human energy needs," and "global climate change." Transcripts were analyzed to categorize the statements counting the total number of concepts mentioned, the number of those concepts that were distinct, and the number of technology/science concepts within the larger set. For example, in the global climate change problem, they found that the freshman engineering students generated around forty total concepts (and around twenty-two distinct concepts). The students generated, on average, slightly less than half of these concepts in response to an initial interview prompt, and thus slightly more than half were generated as the result of probing questions from the interviewer. To increase reliability of the results, all transcripts were analyzed by two coders, interrater reliability was recorded, and all disagreements were negotiated to consensus.

Overall, the study indicated that both engineering and non-engineering students are remarkably similar in their knowledge frameworks. Because both groups were freshmen, specific disciplinary knowledge may not yet have been developed in their conceptual frameworks. In quantitative and comparative terms, the researchers noted that: "In the Human Energy Needs interviews the engineering students mentioned more technological concepts and the non-engineering students mentioned more societal concepts .... However, the same trend is not observed in the Global Climate Change data, and both groups of students show similar trends when we analyzed the mentions of technological and societal problems and solutions. In addition, the content of the knowledge framework for both student groups is almost identical. Finally, both student groups display a general attitude that science and technology play a positive role in society" [23, p. 323].

On a descriptive level for the human energy needs interviews, these researchers noted that the concepts mentioned by students covered the need for energy (e.g., heating, personal automobile, lighting), possible sources and technologies (e.g., nuclear, solar, oil, coal), energy production, conversion, and distribution, energy use (e.g., waste of energy, electricity consumption), impacts (e.g., resource depletion, pollution, standard of living), and mitigations (e.g., conservation, new technology, and choice of energy technology). They also noted that of the concepts generated by the freshman engineering students, 37.2 percent related to technology and 36.6 percent related to society.

5) Characteristics of freshman engineering students: Models for determining student attrition in engineering (Besterfield-Sacre, Atman, and Shuman [24]): This research investigated engineering students' initial attitudes about their own abilities and about engineering (as a field, as an exact science, as a well-paid field), and how those attitudes correlated to retention in engineering programs. The researchers were particularly interested in the attitudes of students who are not retained despite evidence of promise (i.e., those who leave engineering in good standing.)

The researchers developed a closed-form survey with careful attention to the structure and wording of the instrument. Specifically, the researchers used best practice guidelines, item analysis, verbal protocol analysis, and factor analysis to ensure the quality of the resulting instrument. In its final form, the survey included fifty items that cluster into thirteen constructs (e.g., general impressions of engineering, perception of the work engineers do, confidence in engineering skills, confidence in communication skills).

The survey was then administered to all incoming freshman engineering students at University of Pittsburgh (417 students over two years). The researchers found that the students who left engineering in good standing differed statistically from three comparison populations (stayed in engineering in good standing, stayed in engineering in poor standing, left engineering in poor standing). Specifically, the students who left in good standing had lower impressions of engineering, lower perceptions of the work engineers do, lower reported enjoyment of math and science courses, less agreement with the statement that "engineering compares positively to other fields of study," and lower confidence in their engineering skills. In absolute terms, the results indicated that the students who left in good standing were, on average, more likely to respond to these items in a neutral manner (3.5 on a scale of 1 to 6), while the other students in the other populations were more likely to respond, on average, with a low level of agreement (4 on a scale of 1 to 6).

Across all populations and all survey constructs, students' responses ranged, on average, from low levels of disagreement (2 on a scale of 1 to 6) to low levels of agreement (4 on a scale of 1 to 6). The questions about whether family had influenced their choice to study engineering received the most disagreement, with students on average indicating moderate levels of disagreement (2 on a scale of 1 to 6). The highest average levels of agreement (in this case only slight agreement, 4 on a scale of 1 to 6) were in response to the questions about general impressions of engineering and perception of the work that engineers do.

6) Outcomes assessment of engineering writing at the University of Washington (Plumb and Scott [25]): This study investigated portfolio assessment as a means for characterizing engineering writing capabilities at the college level. The work proceeded in two phases: the development of a rubric for analyzing portfolios of writing samples and then the use of the rubric to characterize the writing abilities of engineering students. The development of the rubric was a collaborative effort involving representatives from multiple engineering departments, the university's evaluation group, and the department of technical communication. The resulting outcomes were divided into two categories, principles (broad concepts and attitudes about writing) and qualities. The seven principles identified by the team addressed the issues of audience, purpose, usability, document types, process, career, and confidence. The team also identified approximately thirty aspects of good writing related to the following six dimensions: content, organization, style and tone, fundamentals, audience-appropriateness, and ethics.

In the second stage of the work, the researchers made overall judgments (strong, high competent, competent, low competent, not acceptable) on 122 writing samples from previously collected portfolios and also evaluated each writing sample using the six qualities/thirty dimensions of good writing as a rubric. Overall, the researchers found 67 percent of the writing samples to be in the categories of competent, high competent or strong, but were disappointed that 16 percent of the samples were categorized as not acceptable. On a more detailed level, the authors report the ten most frequently violated aspects of good writing. These weaknesses included failure to include citations and improper citation form (~90 percent), lack of thoroughness in supporting the purpose (~80 percent), incorrect use of conventions such as spelling, grammar, usage, and punctuation (~80 percent), inadequate use of graphs, charts or equations to improve clarity (~55 percent), failure to exhibit a logical progression and structure (~50 percent), and a lack of a clear statement of purpose and justification for the writing (~40 percent). In commenting on the results, the authors observed that, "these weaknesses span a broad range of writing issues and include all of the four areas on which we focus our technical writing instruction: content, organization, design, and mechanics/style. The breadth of the weaknesses seems to indicate that some of our engineering students simply need more practice. They also may need more individual help and feedback with their writing" [25, p. 336]. On a more positive note, the remaining aspects of writing represented in the rubric seem to have been problematic for less that 25 percent of the writing samples.

7) From the students' point of view: Experiences in a freshman engineering design course (Courter, Millar, and Lyons [26]): In this paper, the researchers report on students' experiences in a freshman design course and the effect of the course on retention. Interviews with twenty-eight students conducted in the middle and at the end of the course were the primary source of data. The researchers supplemented these interviews with two focus groups, a written survey, classroom and laboratory observations, and collection of written documents, including course notes, assignment sheets, and handouts. The collection of multiple sources of data made it possible for the researchers to triangulate findings (find evidence for a finding across multiple data sources). The researchers analyzed the data using a grounded theory approach, in which they let the key findings emerge from the data.

The researchers report on six themes that emerged through their analysis: (1) teamwork, (2) a "real-world, hands-on, customer-based" project, (3) a context for engineering as a career, (4) confidence and self-esteem, (5) perceptions of the role of faculty, and (6) stronger friendships among class members. Although these findings are not explicitly about characterizing knowledge, they do provide insights in this area. For example, the finding that "students gained a context for engineering which gave them the motivation to pursue an engineering career" suggests that students did not enter the course with such knowledge and also that they were capable of acquiring this knowledge through an instructional experience. The findings related to teamwork also shed light on the initial and final states of student knowledge about teamwork:

"Teamwork was the focus of much of the students' interviews and was clearly the most important part of their experience. The teams did not function efficiently from the start, but went through a development phase as students got to know each other and became 'more willing to listen to everyone.' 'At the beginning [the course was] kind of weird, you know, because you really didn't know anybody.' Many students were initially skeptical of teams, thinking that they 'could never get anything done.' Most found that their teams worked well, with many noting that working in teams allows individual students to 'take on a specific task that they were stronger in,' and jointly accomplish more than they could individually" [26, p. 285].

8) Higher-order thinking in the unit operations laboratory (Miller, Ely, Baldwin, and Olds [27]): In this paper, the authors focus on the challenge of helping students in chemical engineering develop higher-order thinking skills, a course designed to address this, and examples of how students' higher-order thinking evolves in the context of the course. The course of interest is a summer long field session at Colorado School of Mines in which senior chemical engineering students collect data, perform data analysis, and report it over a six-week period. In their work, the authors operationalize higher-order thinking as thinking that is consistent with higher levels of Bloom's taxonomy (synthesis and evaluation) relative to the middle levels (analysis and application) and the lower levels (knowledge and comprehension).

To characterize students' ability to think at the higher levels of Bloom's hierarchy and how their ability to think changes over the term, the researchers explored laboratory reports from their course to link the statements in the reports to the levels of Bloom's hierarchy. The researchers suggest that student skills in the course develop through the following progression: (1) initial reporting of facts and results only, with no detailed interpretation; (2) elementary data analysis, in which students begin to search for trends and correlations among experimental variables; and finally (3) developing inferences and evaluating results critically. In the paper, these various stages of ability are illustrated through example statements taken from laboratory reports. According to the authors, "The process is developmental, slow, and at times frustrating and painful for some students. But we have found that all students in the course, regardless of academic preparation and background, can improve their ability to think and communicate if given appropriate feedback and encouragement by faculty supervisors and peers" [27, p. 149].

9) Educating effective engineering designers: The role of reflective practice (Adams, Turns, and Atman [28]): This paper presents the results of a body of work on engineering student design behavior and interprets the results through the lens of Donald Schön's *Reflective*

Practitioner. The body of work consists of verbal protocol studies of students performing design activities. The aggregate dataset includes data from (1) ten freshman engineering students solving three "short" design problems, (2) twenty-four freshmen and twenty-six seniors solving a "long" design problem, and (3) sixteen freshmen at the beginning and end of their first semester, and sixty-one seniors, solving three "short" design problems, including within-subjects data from eighteen subjects. Verbal data were transcribed, segmented, and coded according to multiple design-related coding schemes.

Through their prior analyses of the data, the researchers found that students' design behavior changes over the course of their undergraduate education. According to the authors, "Together, these studies demonstrate that measurable differences exist in student design processes after three interventions: (1) after the first semester of a freshman year, (2) after a short-term intervention of reading a text book, and (2) after completing an undergraduate engineering degree" [25, p. 279]. Example measures of design behavior where change was found include time spent solving the design problem, number of transitions, transition rate, number and type of iterations, amount and type of information considered, number of design criteria considered, and progression to later stages of the design process. When information-gathering behavior was studied in more depth, several differences were identified. According to the authors, "the findings illustrate that (1) seniors gathered more information covering more categories than freshmen, (2) seniors made more assumptions than freshman, and (3) both groups failed to collect important types of information, such as legal and maintenance issues" [28, p. 279]. A number of other detailed analyses were done, including studying iterative processes in design activity, evolving design solutions, breadth of problem perception, and others. For further information, see Atman and Turns [33], Atman et al. [34], Adams [35], and Bursic and Atman [36].

In the paper presented here [28], the authors interpreted the findings of their empirical studies from the point of view of the role of reflective practice in engineering education. Using Schön's model, the authors specifically address two of Schön's descriptors of a reflective practitioner—the recognition of the importance of problem setting and the importance of listening to the "back talk" of a situation. The authors found support for both of these descriptors in their data. Specifically, "Schön states that problem setting is 'a recognized professional activity'. In our data we have found that students who have more experience (seniors) display more problem setting behaviors, and therefore are potentially acting more like professionals" [28, p. 285]. In addition, "Schön describes the process of reflection-in-action as beginning with an unexpected event that triggers a shift in a mode of analysis that stimulates a reflective and transformative conversation with a situation's back talk.… In our data, we found that central features of iterative activity map well to elements of this process. More specifically, the bulk of iterative activity resulted in coupled revisions across problem and solution elements, and these events were predominantly triggered by self-monitoring, clarifying, and examining cognitive activity" [28, p. 291].

10) Of green monkeys and failed affordances: A case study of a mechanical engineering design course (Newstetter [29]): This paper focuses on the ability of engineering students to engage in engineering design activities and the aspects of design that students find particularly challenging. To explore this issue, the researcher used ethnographic methods (interviews, participant observation) to collect data in a junior-level mechanical engineering class during a single academic term. Observations of a single design team, and periodic interviews with the team members, formed the core of her data collection. She supplemented this data with classroom observations and interviews with the instructor and other students. Consistent with the ethnographic approach, the data were analyzed in an inductive manner with research findings emerging from the data.

Student challenges with inscriptional systems (conventions for representing information such as a Gantt chart or a standard optimization problem) and with the ideas of distributed intelligence (a key to effective teamwork) form a core of her findings. Here, we focus on the findings related to inscriptional systems. A key to inscriptional systems is that the effort invested in using the inscriptional system is balanced by the benefits of using the system (e.g., seeing specific patterns, getting answers to specific questions). The class had been designed to help students practice using a large number of inscriptional systems and also to practice moving between these inscriptional systems (e.g., moving from a graphic representation of a design alternative to a mathematical equation for determining specific parameters for the alternative).

The researcher noted in her findings that "there were times in the term when students on the observed team maneuvered easily between these differing representations of knowledge and understood their role in the whole design process. However, there were four times when students missed the affordance of a representation. These occurred in a) transforming conceptual problem understanding to graphic representation of problem space using the seven management and planning tools from TQM, b) transforming the preliminary design concept to computer- mediated decision support problems, c) transforming the design concept into mathematical notations, and d) transforming linear equations, representing feasible design space, to hard prototyping" [29, p. 123–124]. The paper describes each of these instances in some detail and also provides suggestions for how educators could address these issues in their teaching.

11) A tool to measure adaptive expertise in biomedical engineering students (Fisher and Peterson [30]): Adaptive experts are those experts who are capable of using existing knowledge to solve new problems, particularly in cases where they lack important information. In this paper, the authors report on research into the development of an instrument to measure potential for adaptive expertise and use of the instrument to characterize engineering students and faculty in these terms.

The first phase of the research was the development of a survey instrument to measure potential for adaptive expertise. Based on a literature review, the researchers defined four primary constructs associated with adaptive expertise: multiple perspectives, meta-cognition, goals and beliefs, and epistemology. They created an initial survey with 100 items and then used two rounds of validation to reduce the survey to forty-two questions. In the first round of validation, the researchers reduced the survey to eighty-four items based on extensive feedback from four representative users. In the second round of validation, the researchers further reduced the survey to forty-nine items based on responses from students in two undergraduate courses as well as from several faculty.

The second phase of the research was the use of the survey to characterize the potential for adaptive expertise among engineering students and faculty. To do this, the researchers collected data from freshmen across multiple engineering majors (N = 209), freshmen in biomedical engineering (N = 37), seniors in biomedical engineering (N = 44), and faculty in biomedical engineering (N = 17).

Overall adaptive expertise scores were higher for seniors than for freshmen and higher for faculty than for seniors, indicating a development of adaptive expertise: "Specifically, the results suggest that adaptiveness increases as individuals progress from initial student to graduating senior to engineering faculty" [30, p. 13]. From the perspective of individual constructs, the data showed a statistically significant increase from freshmen to seniors in two areas: the multiple perspectives construct ("the willingness to use a variety of representations and approaches when working within the domain" [30, p. 4]), and the goals and beliefs construct (whether students "view challenge as an opportunity for growth … to proceed in the face of uncertainty" [30, p. 4]). Meta-cognition construct scores ("the learners' use of various techniques to self-assess and monitor his/her personal understanding and performance" [30, p. 4]) and epistemology (whether students "see knowledge as an evolving entity rather than a static destination" [30, p. 5]) were similar between freshmen and seniors.

The results can also be used to characterize the specific populations in more absolute (less relative) terms. For example, the freshmen students had a weak-to-moderate level of agreement to the epistemology-related questions (sample mean of 4.59 on a scale of 1 to 6) and neutral to weak agreement on the multiple perspectives questions (sample mean of 3.72 on a scale of 1 to 6).

12) A longitudinal and cross-sectional study of engineering student intellectual development as measured by the Perry model (Marra, Palmer and Litzinger [31]): In this paper, the researchers focused on the intellectual development of engineering students captured via the Perry model. "The Perry model suggests that students' cognitive processes develop over time from simple black/white thinking to a more complex evaluation of alternatives. Students' cognitive levels are assessed by a structured interview which asks them to reflect on the ways they think about ambiguous intellectual problems" [31, p. 1]. The interviews are analyzed by experts and each student is given a score that ranges from 1 to 9.

This paper reports on a subset of data from a larger study design that includes student samples from the freshman, junior, and senior classes in addition to graduates of the program. Here, they describe data collected from fifty-three freshman engineering students who were administered the structured interview.

The results of the data analysis show that "…the majority of the students in the first-year sample were at Perry level 3 and 4 (multiplicity). To varying degrees, these students are willing to consider multiple answers but expect their teachers to be a source for finding the right answer from the various possibilities. None of the students in the first-year sample were rated above Perry level 4" [31, p. 8]. The authors note that a Perry Position of 6 is what would be expected of a typical entry-level professional.

AUTHORS' BIOGRAPHIES

Jennifer Turns is an assistant professor in the Department of Technical Communication at the University of Washington. She holds a Ph.D. in industrial engineering from the Georgia Institute of Technology. Her interests include cognitive processes in design, user-centered and learner-centered design, engineering education, and cognitive processes in teaching.

Address: Box 352195, University of Washington, Seattle, WA, 98105; telephone: (206) 221–3650; fax: (206) 221–3161; e-mail: jturns@u.washington.edu.

Cynthia J. Atman is the founding director of the Center for Engineering Learning and Teaching (CELT) in the College of Engineering at the University of Washington and the director of the NSF-funded Center for the Advancement of Engineering Education (CAEE). She is also a professor in Industrial Engineering. Dr. Atman received her Ph.D. in engineering and public policy from Carnegie Mellon University, her M.S. in industrial engineering from Ohio State University, and her B.S. in industrial engineering from West Virginia University. Dr. Atman conducts research on engineering design and engineering learning.

Address: Box 352183, University of Washington, Seattle, WA, 98105; telephone: (206) 616–2171; fax: (206) 221–3161; e-mail: atman@engr.washington.edu.

Robin Adams is the assistant director for research at the Center for Engineering Learning and Teaching (CELT) in the College of Engineering at the University of Washington. She holds degrees in mechanical engineering, materials science and engineering, and education. She is also the lead for the Institute for the Scholarship on Engineering Education (ISEE) as part of the Center for the Advancement of Engineering Education (CAEE). Dr. Adams' research concentrates on understanding engineering learning and strategies for promoting leadership in engineering education.

Address: Box 352183, University of Washington, Seattle, WA, 98105; telephone: (206) 616-0615; fax: (206) 221-3161; e-mail: radams@engr.washington.edu.

Theresa Barker is a graduate student in industrial engineering at the University of Washington. She has a B.S. in mathematics from the University of Washington, and has more than twenty years of experience in industry, including agriculture, aerospace, and software development.

Address: Box 352183, University of Washington, Seattle, WA, 98105; e-mail: barkertj@u.washington.edu.