AC 2007-1505: BREADTH IN DESIGN PROBLEM SCOPING: USING INSIGHTS FROM EXPERTS TO INVESTIGATE STUDENT PROCESSES

Andrew Morozov, University of Washington

ANDREW MOROZOV is a graduate student in Educational Psychology, College of Education, University of Washington. Andrew is working on research projects within the Center for Engineering Learning and Teaching (CELT) and the Center for the Advancement of Engineering Education (CAEE).

Deborah Kilgore, University of Washington

DEBORAH KILGORE is a Research Scientist in the Center for Engineering Learning and Teaching (CELT) and the Center for the Advancement of Engineering Education (CAEE), University of Washington. Her areas of specific interest and expertise include qualitative and mixed educational research methods, adult learning theory, student development, and women in education.

Cynthia Atman, University of Washington

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). Dr. Atman is a Professor in Industrial Engineering. Her research focuses on design learning and engineering education.

Breadth in Design Problem Scoping:
Using Insights from Experts to Investigate Student Processes

Abstract

Because design plays a central role in engineering, it is important for engineering education programs to prepare students with design skills. By describing both novice and expert approaches to engineering design, researchers are contributing to the formulation of more specific design learning outcomes that may be addressed in curriculum design and program planning. One learning area where novices and experts differ is in how broadly they define engineering problems with which they are faced. This paper examines differences between how novices and experts approached the same hypothetical engineering problem. First-year students (n=124) and experienced engineers (n=4) were asked to identify factors they would take into account when designing a retaining wall system for the Mississippi River. Expert data were gathered using verbal protocol analysis, in which subjects were asked to “think aloud” as they addressed the retaining wall problem, and their statements were coded and interpreted. Novice data were gathered using a written protocol in which subjects were asked to simply list the factors on paper. Qualitative data were segmented into distinct ideas, which were then coded using a coding scheme with two dimensions of problem scoping breadth: physical location and frame of reference. We found that novices offered a greater proportion of factors from the natural and social frames of reference, versus technical and logistical frames, which indicated a rather broad approach the problem. We argue that this may reflect the novices’ relative inexperience with engineering concepts. While the four experts’ responses differed in terms of their representations through a “breadth of problem scoping” coding scheme, two of the responses echoed a characteristic top-down, breadth-first approach to design. The difference in protocols presents challenges in comparing expert and novice behavior, and methodological issues of collecting less information from a greater number of subjects versus collecting more information from fewer subjects were addressed. Because asking the experts to think aloud resulted in a rich data set, we employed narrative analysis to further investigate expert responses. The narrative analysis of expert problem scoping behavior suggested a sophisticated approach to situating problems and solutions in context. It highlighted several particular kinds of factors that the four experts in our sample were drawn to – existing engineered solutions, alternative design solutions, costs and benefits, priorities, and history. In addition, the narrative analysis illustrated the relationships between and among an expert’s ideas, and what these relationships imply for the expert designers’ thought processes.

Introduction

Design plays a central role in engineering, and teaching and learning good design skills are important aspects of engineering education in colleges and universities[1,2]. ABET has recognized this need by including “an ability to design a system, component, or process to meet desired needs” among its eleven learning outcomes[3]. This emphasis on students’ development of design abilities raises questions about what these skills and knowledge actually encompass. What skills and knowledge are necessary for designers to design well? A key challenge, then, is the identification of specific design learning outcomes that indicate a student has become competent to design well. To accomplish this, it is necessary to understand the properties of good design.

One way to identify design knowledge and skills is to look at how design is practiced by "experts;" in this case, those who are considered so based on their years of experience in the profession creating successful engineering designs. Insights from the approaches that expert designers take to analyze a problem and develop design solutions can inform researchers and educators about the skills and knowledge students should acquire to become competent designers. Research on expert design thinking and doing is expected to contribute to the formulation of more specific design learning outcomes that may be addressed in curriculum development and program planning.

The exploratory study discussed here offers an in-depth look at how four expert engineers address a specific design task. Using a mixed methods approach to data analysis, we will (1) compare expert behavior to that of novices who participated in another study, and (2) begin to develop a narrative theory of experts' ways of thinking about and doing design. Verbal protocol analysis has allowed us to use an existing coding scheme for making systematic comparisons across research studies that have generated relatively large datasets on design thinking and doing[4]. This component of the current study contributes to our ongoing larger program of inquiry aimed at establishing an empirical foundation for directing instructional development in college-level engineering design education. A second research method used here, narrative analysis, allows us to identify additional ways of thinking about and doing design not captured by the coding scheme, and suggests new directions for future research.

Literature Review

It is widely acknowledged that contemporary engineering must be studied and practiced in context. The National Academy of Engineering (NAE) proposes an "Engineer of 2020" who demonstrates the knowledge, skills and attitudes necessary to design for an uncertain and rapidly changing world[5]. Contextual conditions like a fragile global economy, increased mobility of jobs and workers, rapid development of information and communication technologies, growing calls for social responsibility[6], and rising complexity of engineered products[2] all warrant engineering students' development of skills with which to situate their technical work. Furthermore, the increasingly diverse engineering workforce and marketplace require "cultural competence"; that is, a willingness and ability to consider culture in engineering problem-solving[7]. Therefore, our definition of engineering design expertise should include an ability to design in context.

It is generally assumed that in any given field, people begin as novices and as they practice over time, develop into experts[8,9]. An expert is an individual who consistently performs with a high level of skills, often at a higher level than others in the same field[10]. Many studies of engineering design behavior have elucidated the design activity of problem framing, both as it is exhibited by experts[11] and as problem definition is associated with more effective student designers[12]. Experts are expected to scope a problem in such a way that they adequately account for context. Problem scoping refers to the portion of the design process where designers define the nature of the design problem and the space in which they will search for design solutions. This often involves gathering information from a broad range of sources, framing the requirements of design solutions, clarifying and prioritizing these requirements, and determining the needs of the intended user. To keep up with the accelerating pace of technological progress and increasing magnitude of the impact of engineering on society[5], engineers need to think broadly when they are scoping design problems. Understanding how experts scope and situate design problems and solutions (in the larger context) may suggest ways to improve engineering education with targeted consideration of contextual issues. The present study is part of a series of empirical efforts to develop ways of understanding and measuring breadth in problem scoping.

Objectives of the Study

This paper pursues two main objectives. First, we characterize expert design thinking in terms of breadth of problem scoping. We will use a data reduction framework that has been developed over the course of several previous studies of student design processes[13-16]. To put the results of our analysis of experts' design approaches in perspective, we refer to the first-year data from the Academic Pathways Study, which uses the same framework to explore the problem scoping activity of freshman-level engineering students. Due to differences in the ways the data were collected in each of these studies, as described later in this paper, no direct comparison between these datasets is performed. Our goal in quantifying the expert responses within an established analytical framework is to check for common features across the expert "cases" with regard to the breadth of problem scoping, as defined by a specific coding scheme. We reference the analysis of the student data to situate these results relative to a "novice" dataset, explored through the same analytical lens.

Second, we concentrate our attention on the expert responses to see whether they reveal any interesting and/or consistent problem frames or reasoning patterns, which may be unaccounted for in applying the coding scheme as defined. We do this by examining the expert responses using narrative analysis.

This study addresses the following research questions:

1. What are expert ways of thinking about a problem scoping design task?
2. Are there regularities among expert responses with regard to the breadth of problem scoping?
3. Are there qualities of expert thinking that can inform how we understand novice thinking?

Methods

In this study, we use two means for analyzing the expert data: verbal protocol analysis and narrative analysis. Verbal protocol analysis has been effectively used to describe the design processes employed by engineering students[17-19], as well as expert designers[11, 20-22] and more specifically, expert-novice comparative research upon which the current study is based[23,24]. Narrative analysis[25] entails a close reading of the transcripts, not only seeking to identify content categories, particularly those not highlighted in the VPA, but also to trace the logic or structure underlying the respondent's answer.

A. Participants

The expert data used for this study came from a subset of four responses (n=4) purposefully selected from a pre-existing pool of responses of 19 experienced engineers. The original 19 are experienced practicing professional engineers who were identified by their peers at work as expert designers. All participants initially completed a screening survey, indicating their education and employment background. According to their stated undergraduate majors, the group represents six engineering specializations, and their experience in the field ranges from 7-32 years, with a mean of 19 years. The sample consists of fourteen white males, three Asian/Pacific Islander males, and two white females. Each participant was compensated $100 for participating in the study.

One of our main objectives in selecting the four respondents to be discussed here was to choose the "most expert." To accomplish this, we considered their years of professional experience, as well as responses to a "playground design" task, which they completed prior to the task discussed here. In that task, they were asked to list the types of information they would need to design a playground, and asking for more types of information was considered an indicator of expertise[23,24]. Our second objective was to choose respondents such that we maximized diversity of perspectives. To accomplish this, we purposefully included one of the women among our four, and selected diverse participants based on their area of engineering specialization. Table 1 provides an overview of the expert participants discussed in this study.

Table 1. Expert Participants

ID	Participant Pseudonym	Area of Specialization	Years of Experience	Sex	Number of types of info requested
01-01	Ann	Industrial Engr.	22	F	8
07-35	Eric	Mechanical Engr.	29	M	9
12-57	John	Systems Engr.	32	M	10
18-84	Peter	Civil Engr.	24	M	8

B. Procedure

The expert design activity was recorded and analyzed using verbal protocol analysis[26]. Verbal protocol analysis involves asking participants to "think aloud," while performing a design activity. Verbal protocol analysis has been validated as a means to elicit and analyze the cognitive process, such as reasoning involved in design activity[26]. A widely used means for studying design thinking, it has been instrumental in the analysis of performance on specific design tasks[27]. In this study, VPA was implemented by asking participants to think aloud as they addressed the following design task:

> "*In the past, the Midwest has experienced massive flooding of the Mississippi River. What factors would you take into account in designing a retaining wall system for the Mississippi?*"

The Midwest floods problem (MWF) has been used in previous studies of design behavior in engineering students[13,15,28]. It allows participants to engage in "extensive problem definition in the context of a broad-based real-world problem"[26]. The problem is intended to provide a problem-scoping goal orientation, directing respondents to think about the constraints, or factors, to be considered given the proposed solution approach.

The Midwest floods problem was the third task in a series of tasks. In the first task, the participants were asked to design a playground, and in the second task they were asked to read and comment on a model of the engineering design process. The experts were then prompted to read the Midwest floods problem statement aloud, and to think aloud while responding to it. In addition, sheets of paper with the problem statement were provided, and the experts were told that they could write down the factors on paper in addition to describing them verbally, should they choose to do so. This written data is not included as part of this analysis. Each participant worked individually, and the administrator provided no further information or feedback during the exercise. Each expert had up to 30 minutes to complete the design task. The verbal responses were audio recorded and transcribed for subsequent coding and interpretation.

C. Analysis

Data Reduction using Verbal Protocol Analysis

The analysis data for each expert participant consisted of a transcribed response to the verbal protocol on the Midwest floods design task. Each transcript was segmented by two research assistants into distinct "thought units," or ideas. The segmented statements were compared and any inconsistencies or disagreements negotiated, producing the final segmented version of the transcript.

Verbal protocol analysis often involves the application of a coding scheme, in order to systematically measure and categorize design processes[26,29,30]. The analytic framework used for verbal protocol analysis in this study is based on a "breadth of problem scoping" coding scheme for the MWF problem, originally developed to analyze the problem scoping behavior of engineering students[13].

The statements from the segmented transcripts were coded on two dimensions of problem scoping breadth: physical location and frame of reference. The physical location codes indicate the physical focus of each idea: on the wall itself, the water, the riverbank, or the wider surroundings beyond. The frame of reference codes indicate the perspective represented in each idea: technical, logistical, natural, or social. A summary of descriptions for each code is provided in Table 2. The movement from "wall" to "surroundings" on the physical location dimension reflects consideration of a broader physical context, and the movement from "technical" to "social" frame of reference reflects consideration of a broader social context of the design (see Bogusch, Turns, and Atman[13] for a full description of this coding scheme).

Table 2. Descriptions of codes for MWF problem.

FRAME OF REFERENCE	DESCRIPTION
Technical	Technical or engineering vocabulary, design issues, decisions about having the wall.
Logistical	Cost, funding, construction process, maintainability issues, resources

	needed.
Natural	Volume of water, damage, effects of flood, topography, animals, plants, weather and weather predictions.
Social	People, safety concerning people, towns, living areas, fields of engineering and education.
Physical Location	**Description**
Wall	The wall itself, things that interact with the wall, alternatives for having a wall, where to put the wall.
Water	Length of the river, fish, flood without effects, pressure issues without mention of the wall.
Bank	Interface of the wall, edge of the river, width of the river.
Surroundings	Anything away from the water, living areas, things along the water, specific effects of the wall or flood to the shore.

Coding was conducted by a team of one graduate and two undergraduate research assistants. Each transcript was first coded individually by two members of the team. The inter-rater reliability was estimated by dividing the number of identically coded statements by the total number of coded statements, excluding any "non-applicable" statements not coded using the coding scheme. Coding a sample of one out of the four verbal transcripts produced an average inter-rater reliability estimate of 77%. The average reliability after coding all four transcripts was 72%. After all individual coding was completed, coders negotiated discrepancies and came to consensus.

Narrative Analysis

Verbal protocol analysis can provide a way to analyse verbal data at a detailed level – where a phrase or a sentence illustrates one particular idea. This is a useful and rigorous lens for making systematic comparisons of the content of ideas between subjects and across samples. Narrative analysis is another lens that brings into clarity the relationships between and among those ideas, and the thinking processes that led to the unfolding of those ideas.

Narratives – the stories we tell ourselves and others – are present in every aspect of society[25]. A narrative is generally defined as the telling of a sequence of events or ideas that are bound to one another coherently[31]. Whether knowing and action are habitual or spontaneous, sequential or simultaneous, narratives are an imposition of order. In other words, narratives are the way people know the world, so it makes sense to study the world narratively[32]. By doing a close reading of the full narratives of experts as they encounter and engage with the Midwest Floods Problem, we can better observe and understand their *knowing-in-action*[33]; that is, the way they organize their knowledge as they proceed in problem solving.

Two of the authors read the expert transcripts separately, looking for emergent themes and narrative structures. We then shared these exploratory findings with four other researchers and discussed their strength and relevance. One of the authors then did another close reading of the transcripts, identifying places in the narrative where one idea was joined logically with another and where ideas were evaluated by the narrator. For example, the passage:

…given that you have the maps, then you could determine where a logical boundary for the river would be…

was marked in the following manner:

…given that you have the maps [JOIN] then you could determine where a logical [EVAL] boundary for the river would be…

The analyst also took notes of patterns of these "joins" and "evaluations" emerging from the transcripts. In the following section, we will discuss our findings.

Findings

In this section we present our findings about expert designers' approaches to engineering design problem scoping. Using VPA and the coding scheme described above, we will first describe the breadth with which the four experts framed the MWF problem. To put these findings in perspective, we will then compare the four experts' breadth in problem scoping with that found among novices (n=124 freshmen) in the Academic Pathways Study[16]. In the second part of this section, we will present the narrative analysis of expert designers' ways of thinking about the MWF problem. We will provide a brief summary of how this analytical approach may enhance and expand upon the discoveries stemming from VPA.

Verbal Protocol Analysis

In addition to the frame of reference and the physical location codes, three codes were applied when coding expert responses. Two of these indicated "non-applicable" segments falling outside the coding scheme. The first code marked any administrator utterances (e.g., a prompt to read the design task out loud). The second code marked participant utterances which either did not contain meaningful thought units (e.g., "Uh," "Okay," "So," etc.), or contained thoughts which had no connection to the coding scheme (e.g., "That's about all I can think of," "I can't think of any other factors," etc.) A third code marked participant utterances which constituted "equivalent" segments, those that were nearly identical or shared the same meaning with another segment. The total number of segments includes the unique ideas a study participant offered in response to the MWF problem, as well as any "non-applicable" or "equivalent" segments.

None of the experts in the sample used the full 30 minutes they were given to think aloud. Therefore, we assume that they exhausted their stores of ideas about this problem, at least any ideas they would had at the time of the administration of the problem. The tallies of coded statements based on the expert verbal responses are provided in Table 3. The last row, labeled "coded segments used for analysis," shows the number of statements used for all subsequent analysis of breadth in problem scoping. Among the four experts, this number ranges from 20 to 118, with a total of 228 statements.

Table 3. Experts' numbers of segments (individual and aggregate).

Segment Type \ Expert ID	Ann	Eric	John	Peter	Total
Total Segments	32	105	149	52	338

N/A Segments	10	18	22	9	59
Equivalent Segments	2	26	9	14	51
Coded segments used for analysis	20	61	118	29	228

A summary of the distribution of the four experts' statements based on the coding scheme is provided in Table 4. The distributions of the raw statement counts across the coding categories can also be graphically represented by placing each coded statement in the appropriate *node* on the dimension matrix for the coding scheme. The intersections of the nodes with the circles indicate the number of statements with the corresponding codes. Nodes with no associated numbers indicate that this respondent provided no statements coded for that node. The aggregate distribution of coded statements for the four expert participants is shown in Figure 2a.

Table 4. Experts' coded segments (aggregate).

Location \ Reference	Technical	Logistical	Natural	Social	**Grand Total**
Wall	33	55	4	13	105
Water	15	1	20	3	39
Bank	14	0	14	6	34
Surroundings	8	7	3	32	50
Grand Total	70	63	41	54	228

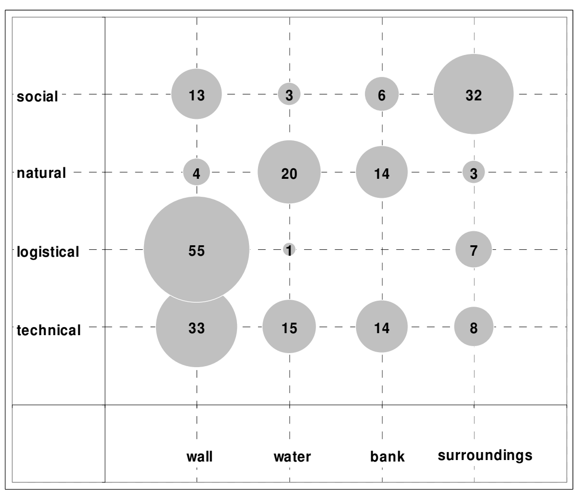

Figure 2a. Aggregate coded statements on MWF task (n=228 statements)

The distributions of the raw statement counts across the *nodes* on the coding scheme for each expert participant are shown in Figures 2b-2e. There is no common pattern among the four experts in terms of the numbers of segments, or the distribution of these segments across the coding scheme.

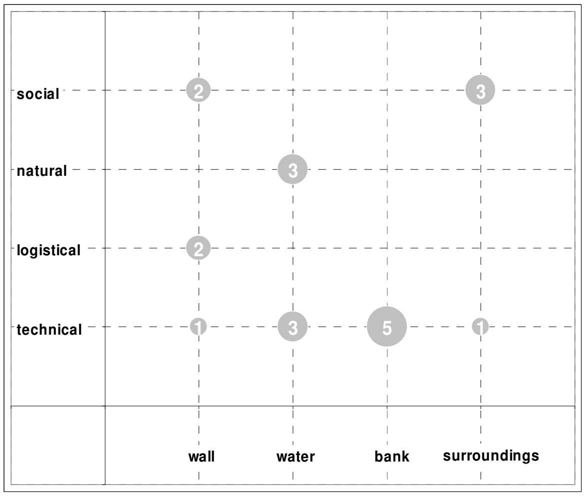

Figure 2b. Ann (n=20 statements)

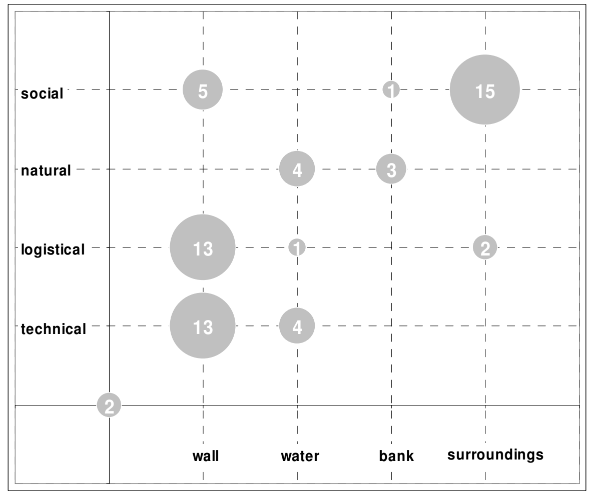

Figure 2c. Eric (n=61 statements)

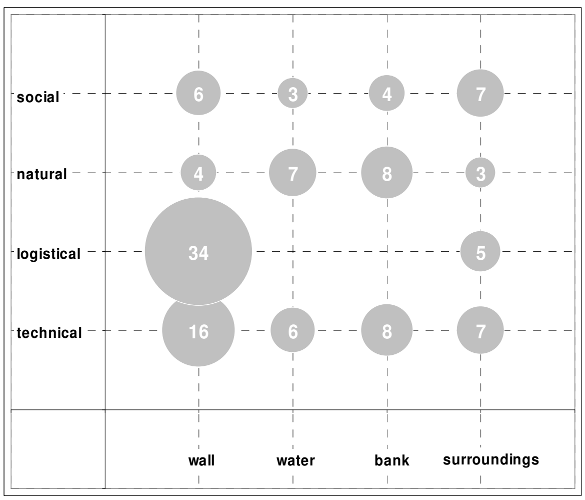

Figure 2d. John (n=118 statements)

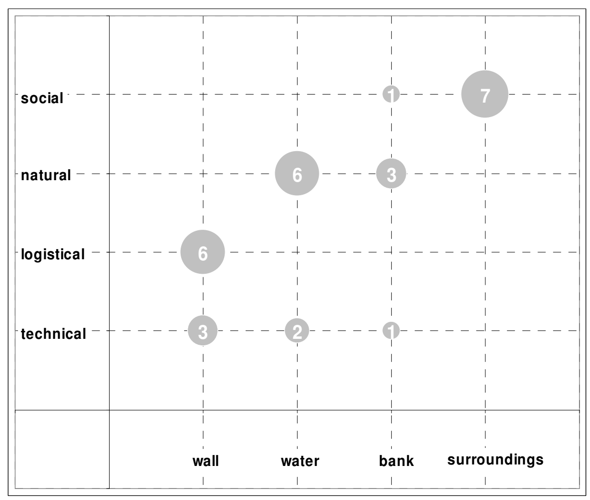

Figure 2e. Peter (n=29 statements)

The concepts of *design detail* and *design context* enable quantification and comparison of the breadth of problem scoping among expert responses. As illustrated in Figure 3, ideas focused on the wall or the water from a technical or logistical perspective were interpreted to be oriented toward the details of the design problem. All other ideas were considered to be oriented toward the context of the design problem. For example, a stated factor such as, "materials for the wall" was assigned the codes "Wall" and "Technical," and therefore interpreted as oriented toward the design detail. This stands in contrast to "people who live in the flood plain," which was assigned the codes "Surroundings" and "Social," and was identified as oriented toward the design context. In the four-by-four matrix of nodes across the two dimensions of the coding scheme, the design detail area includes the 4 inner nodes, and the design context area includes the 12 remaining outer nodes.

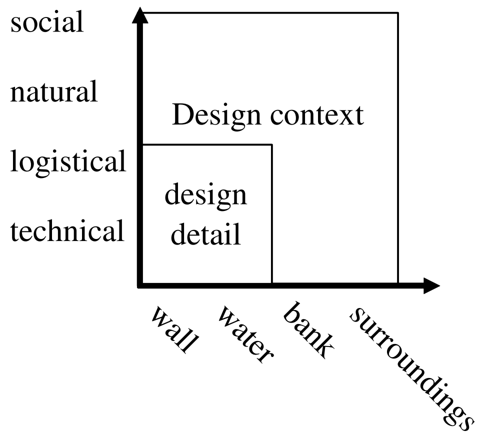

Figure 3: Interpretation of Midwest Floods Problem codes

The aggregate percentages of statements within the design detail and design context areas of the coding scheme are shown in Table 5. Design detail refers to the percentage of statements coded in the 4 nodes, at the intersection of the "wall" and "water" physical locations with the "technical" and "logistical" frames of reference. Design context refers to the percentage of statements coded in the 12 remaining nodes, at the intersection of "bank" and "surroundings" physical locations with the "natural" and "social" frames of reference (design context = 100% - % design detail).

Table 5. Comparison of percentage of design detail vs. design context statements in each expert's response.

	Ann	Eric	John	Peter	Total
Number of statements	20	61	118	29	228
Design detail	30%	51%	47%	38%	46%
Design context	70%	49%	53%	62%	54%

As we can see from the table, the experts with the greater number of segments or unique ideas (Eric and John) considered design detail and design context almost equally. The two experts with fewer unique ideas (Ann and Peter) had a higher proportion of ideas focused on design context. This may be an artifact of the number of ideas given; that is, as the number of ideas increases, the relative proportion of those focused on design detail and design context moves closer to even.

Situating Expert Data in Novice Research

The Academic Pathways Study research element of the NSF-funded Center for the Advancement of Engineering Education is a multi-institution, mixed-method, longitudinal study which examines engineering students' learning and development as they move into, through, and beyond their undergraduate institutions. Data were collected from students at each of four institutions: Mountain Technical Institute (MT), a public university specializing in teaching engineering and technology; Oliver University, a private historically black mid-Atlantic institution; University of West State, a state university in the Northwest U.S.; and University of Coleman, a medium-sized private university on the West Coast (pseudonyms).

The Academic Pathways Study uses a concurrent triangulation mixed-methods design, in which both qualitative and quantitative methods are employed to collect and analyze data.[34] The integration of results occurs during the interpretation phase. This allows researchers to answer a broad range of research questions directed toward discerning complex phenomena like student learning and development.[35] Data were collected from students at the four institutions using surveys, structured and semi-structured interviews, and ethnographic observations. Students were also asked to perform simple engineering tasks during timed sessions at the conclusion of interviews. The study was designed to collect data from forty students at each of the four institutions (n=160). Sample sizes have changed during the first three years of the study as some students transferred out of their schools, the major, and/or the project. Data analysis for each of the methods is ongoing.

During the first year of the study, the Midwest Floods task was administered to 124 freshmen. Instead of thinking aloud, the students were given ten minutes to write down their answers. The transcripts were segmented and coded in the same way as described for the expert data above.

Table 6 contains a summary of the performance of freshman (novices) on the MWF problem in the Academic Pathways Study. The findings from this study are presented in greater detail elsewhere[36].As shown in Table 6 and the corresponding Figure 4, novices' ideas were distributed across physical locations in a similar fashion to those of the experts. As with the experts, about half of the novices' statements were focused on the wall, twice as many as those focused on water. As with the experts, the frame of reference codes are more evenly distributed across the four categories, but the distribution is somewhat different. In particular, novices considered more factors with a natural frame of reference than experts: 30% of novices' ideas were focused on natural considerations, compared with only 18% of experts'.

Table 6. Novice performance on MWF (n=124)

Location \ Reference	Technical	Logistical	Natural	Social	**Grand Total**
Wall	240	360	0	103	703
Water	75	8	220	44	347
Bank	25	13	154	22	214
Surroundings	0	8	57	89	154
Grand Total	340	389	431	258	1418

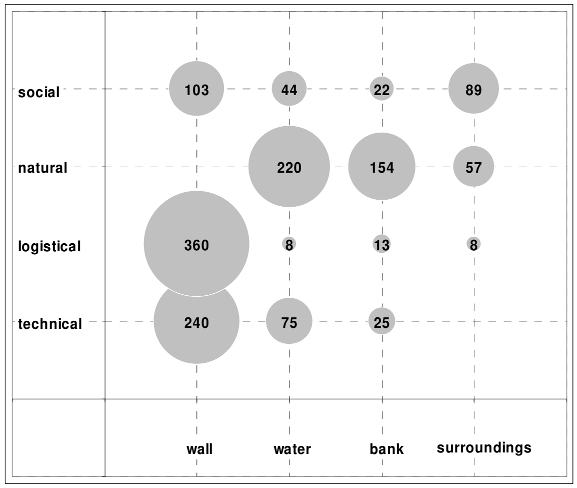

Figure 4. Novices' coded statements on MWF task (n=1418 statements)

A direct comparison of the expert and novice samples can not be made because the methods for collecting data (verbal vs. written) resulted in vastly different numbers of statements. Novices provided 11.5 statements on average, while experts offered 57 statements on average. However, a rough comparison of the distribution of their ideas across the categories may be made. Table 7 shows the percent distribution of segments coded in each of the four frame of reference categories and each of the four location categories, as well as the proportion of segments in design detail vs. context areas for both novices and experts (percents may not add up to 100% due to rounding). In aggregate, novice designers were almost equally focused on design detail and design context, with 48% of statements in the area of design detail and the remaining 52% in the area of design context. As a group, the four experts also exhibited approximately equal focus on design detail and context, with 46% of the statements attributed to design detail, and 54% attributed to design context.

Table 7. Comparison of Expert and Novice performance on MWF

Element	**Novices (n=124, # segments=1418)**	**Experts (n=4, # segments=228)**
Design Detail (%)	48	46
Design Context (%)	52	54
Frame of Reference Codes (%)		
Technical	24	30
Logistical	27	28
Natural	30	18
Social	18	24
Physical Location Codes (%)		
Wall	50	46
Water	24	17
Bank	14	15
Surroundings	12	22

Among the experts, the “wall” makes up nearly half (46%) of statements coded for physical location, and accounts for more than twice the number in the second-largest (22%) category, coded as “surroundings.” The frame of reference codes are more evenly distributed among the four categories, and range from 18% for “natural” to 30% for “technical.” However, these figures do not necessarily suggest that the experts, taken together, followed a “narrow” problem scoping approach, since some of the statements focused on the retaining wall have a broader “natural” or “social” frame of reference, and statements with the “technical” frame of reference have a broader physical scope of “bank” or “surroundings.” Rather, the figures indicate that the statements related to the retaining wall (a total of 105 segments) across all frames of reference, and the statements about the technical aspects of the design (a total of 70 segments) across all physical locations, account for the majority of the factors mentioned by this group of four experts in scoping the MWF problem. It should also be noted that some of the alternatives to a “retaining wall system,” such as the use of sandbags or earthen berms, were coded in the “Wall” category, since they represented “wall-type” approaches to containing the flooding of the Mississippi. However broadly the experts may have defined the problem, the “retaining wall system” remained the dominant theme in their analyses.

Comparing novices to experts, the proportion of the students’ ideas with a natural frame of reference were substantially different, and the proportion of ideas focused on the surroundings were also different. At the same time, the novices’ emphasis on the wall (50%), and the relative amount of these statements compared to the next-largest category of statements related to water (24%), closely match the distribution of these codes in the experts’ statements.

With a larger number of experts (n=19), we hope we can make more meaningful comparisons in the aggregate between expert and novice problem scoping behaviors. However, we are limited by the difference in the two methods used to gather data. Asking the experts to think aloud resulted in a rich data set, and verbal protocol analysis gives us only one lens into how experts think about and do problem scoping. To augment this, we turn to narrative analysis as a method of analyzing the data.

Narrative Analysis

Narrative analysis allows us to take a close look at the data, not only at what is contained in the statements made by the experts, but also how the statements are organized into a larger narrative structure. Because it is a qualitative approach, the insights gained from it must take into account the positionality of the analyst. *Positionality* is the standpoint from which an analyst views the data. The authors come to this analysis from different positions. In particular, two of us had experience with the novice data which influenced how we looked at the experts’ responses, where differences between experts and novices emerged for us first. The other author had relatively little experience with the novice data, and therefore was better equipped in some ways to bring a fresh eye to the expert data.

The verbal protocol analysis was extended through a closer examination of the content of the narratives of the four experts. Five kinds of factors stood out for us, either because they hadn’t seemed as pronounced in the novice data or because they emerged rather strongly in the expert data:

1) The experts suggested looking at existing retaining wall systems and other *existing engineered solutions* for flooding
2) Even though they were not asked to do so, the experts began to consider *alternative design solutions* and wall materials.
3) The experts weighed *costs and benefits* throughout their narratives.
4) The experts considered *priorities* based on costs and benefits.
5) The experts situated their narratives in history. Each narrative had *temporality*: a past, a present, and in some cases, a future.

In addition to these content-oriented observations, we also made the following observations about the experts' thinking processes:

6) One approach to the MWF was to state a broad factor, and then elaborate and expand upon it by brainstorming a list of related detailed factors.
7) Expert verbal responses often included logical connections among sets of related factors.
8) One method of organizing thoughts was to embed a set of related ideas within another set of related ideas.

In the following discussion, each of these themes will be described in greater detail.

Existing engineered solutions

All of the experts thought it was important to look at existing engineered solutions for flooding. For example, Eric speculated, "I would guess they would draw on some standard kinds of designs….There are all kinds of other solutions." Eric's ruminations about alternative design solutions led him to think about the different materials that would be used given a different alternative. "There are…other kinds of combinations of stone and other kind of retaining materials to keep the stone in place. Concrete rubble, amended soils of some kinds, concrete, amended soils…" John, too, would "go look at a bunch of other retaining walls." His reason for examining alternatives was because he knew there were a variety of features that were possible for a retaining wall. "Quite a few that I've seen had berms and have special entrances and exits and they close 'em off during flood season and all that." Ann also considered looking at "whether there's already containment devices and if there are, how they work."

Alternative Solutions

As they considered factors, the experts were logically drawn toward alternative solutions to flooding. Eric provides a good example of this, as he recaps a number of factors he has addressed, and listing these aloud leads him to think of a potential design alternative.

> Available money and labor and time frame. I mean on the cheap and last-minute extreme of things, you know, you could have people that have sandbags. That's a wall. It's not very permanent and it's not very durable, but it may be acceptable.

John also considered alternative designs for the MWF problem. "There's a lot of different configurations of retaining walls. Some are, um, built in place or cast in place, whatever, and some can be, a lot of things are modularly done ahead, dropped in…" After recalling retaining wall solutions he'd seen, John "…wonder[ed] if, if berm, berm, B-E-R-M, berms might be an alternative in some areas. Um, versus retaining wall."

Costs and Benefits

Alternative designs sometimes seemed a natural outgrowth of a thought process that went back and forth between advantages and disadvantages, between benefits and costs. Peter acknowledged that considering existing alternatives was "thinking outside the box." Peter illustrates how the idea to look at existing alternatives can be tied to a related idea to consider cheaper design alternatives to the retaining wall, itself. "We would also want to just consider before we just tie ourselves into retaining walls, expensive retaining walls. There are different types of retaining walls that could work, too, so look at different types of retaining walls, or we can look at alternatives to retaining walls." Other experts, like John, also considered costs and benefits as they thought aloud. "Uh, usually in doing public stuff, and I'm assuming this would be generally public, it'd have uh, maybe some different contract arrangements -- you'd want to have to reduce your costs."

Eric, the expert who had suggested a cheap alternative to a retaining wall could be sandbags, also considered where the money would come from and therefore what the budget for a solution would be. "A town on a limited budget might use the sandbag approach, whereas the federal government may choose to pay for new concrete-lined sections of the river."

Priorities

Like other experts, Eric's talk of costs and benefits was accompanied by ponderings on the question, "Who or what are we trying to protect?"

> I guess one thing that occurs to me as an example is if it were prime farmland, say, that may be periodic flooding might be acceptable, and so the sandbag idea might not be so bad, but if it were a hospital that you were trying to protect, maybe a concrete wall might be worth the money. So, I guess the risk or impact or potential for damage and loss of life, economic loss, those kinds of factors all play into the amount of money that one would want to spend for flood protection.

In asking where the retaining wall should be placed along the river, Ann wanted to know whether the land was "agricultural versus undeveloped…versus residential." Peter also wondered, "Is it a hospital, police station, farmland?" He explained, "We would choose differently depending upon what we are actually trying to protect." John considered priorities, as well. "You probably start big and say, 'Okay, where have been our biggest problems?'"

Temporality

While they considered how other engineered solutions for flooding fared, began to devise alternative design solutions for the MWF problem, examined costs and benefits of various courses of action, and prioritized, the experts also placed the MWF problem in its historical context. A key quality of narratives, in general, is temporality. "Any event, or thing, has a past, a present as it appears to us, and an implied future”[32] . In the case of the expert responses to the MWF problem, as described above, the experts considered current conditions of the problem. In addition, they drew on history to frame the problem, and even implied the future of the proposed solution.

Ann thought it was important to know “history on when it has flooded.” Eric tied the history of flooding to his cost-benefits analysis:

> [You would want to know something about] the frequency of the flooding, because at some point there's a flood event that's so infrequent that you can't afford to protect against it. I mean it might be really huge, but it happens once every thousand years, so then you don't build a structure to protect against that.

So did Peter, who said, “You may not have the money to design for the maximum flood height.” He wanted to know whether “you’re talking about a fifty-year flood, a hundred-year flood, a thousand-year flood.” John was interested in “storm history.” He explained, “You know, ‘cause you want to design it for, I’m assuming, at least 100-year storms.”

Two experts were interested in what had been done before to contain flooding of the Mississippi, as Ann put it, “Whether there’s already levees and dikes and dams and whatever other solutions to floods that are already there.” John asked, “Why haven’t they done it? I guess the sort of history questions, why hasn’t it been done already? Uh, and what’s the overall, I mean, is there already something in place?”

In addition to asking about the past, experts also prepared for the future, at least with respect to maintenance. For example, John said, “You want to know what kind of maintenance is done on the river and what kind of existing systems are available in terms of uh monitoring and, and maintaining a retaining wall.” Furthermore, the cost-benefits analysis and evaluation of possible alternative solutions also imply future outcomes.

Developing narrative sets of related factors

Often, experts developed what we are calling a *narrative set of related factors* by beginning with a broad factor that placed temporary bounds around their thinking, and then elaborating on that broad factor with a list of related detailed factors. For example, John created a set of related factors having to do with the Army Corps of Engineers:

Table 8. A narrative set of related factors.

Factor Type	**Narrative Segment**
FRAME	*it’s a Corps of Engineers project probabl*y
	so, I’d obviously talk to the Corps of Engineers
ELAB	and find out, you know, what, what’s been going on
ELAB	and what their standards are.
ELAB	There’re probably a lot of standards
	I’m assuming for the retaining walls along rivers,

ELAB	and uh tests that need to be conducted,

As we can see from the passage in Table 8, John provided what we are calling a framing factor (FRAME)-- “it’s a Corps of Engineers project probably” and then elaborated on what that would mean in terms of solving the MWF problem. The “elaborating factors” (ELAB) are: “what’s been going on,” “what their standards are,” “There are probably a lot of standards…for retaining walls,” and “tests that need to be conducted.” Figure 5 is a graphic representation of a narrative set of related factors. The framing factor is often, but not necessarily always, the first narrative segment in the set, and then the meaning of the framing factor is elaborated upon and enriched with one or more elaborating factors. The narrative set can be understood as a framing factor with one or more elaborating factors embedded within it.

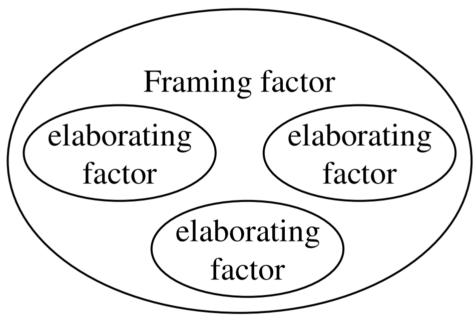

Figure 5. Illustration of a narrative set of related factors.

Connecting sets of related factors logically

As experts created narrative sets of related factors, they also were inclined to connect these narrative sets to one another in various ways. Eric provides an example of how two narrative sets of related factors are logically connected, as shown in Table 9. The first narrative set has to do with floodplain maps, and what kinds of information these will give the designer and how they will influence decision decisions. The second narrative set is on the topic of protecting man-made structures near the river from flooding. Each set contains a framing factor and one or more elaborating factors.

Table 9. Two narrative sets are logically connected.

Factor Type	**Narrative Segment**
FRAME 1	I'd look for something that has floodplain maps on it
ELAB 1	and historical data as to where the historical boundaries of the river are.
ELAB 1	There's no sense building a wall that's in the middle of the river at the 25-year flood or something,
ELAB 1	because you won't be able to contain it
ELAB 1	So given that you have the maps,
ELAB 1	then you could determine where a logical boundary for the river would be,
ELAB 1	and that's where you would set the wall to contain it.
ELAB 2	I don't believe this is a problem to channelize or provide a levy or dike along the entire length of the river,

FRAME 2	so I'm going to assume that the idea of the wall is to protect man-made structures along relatively short portions of the river...
JOIN	Okay. So you've got some historical maps…
JOIN	you've got to find out where the man-made structures are that you're protecting.
FRAME 3	So now you have some rough idea of where the wall would be.

Of interest here is how the two sets are connected to one another logically. In this instance, the two sets are connected as two broad factors that must be considered together to determine where to build a retaining wall. The passages indicated as "JOIN" factor types are those that contributed to the logical joining of the two narrative sets. In this case, Eric joins the narrative set about "floodplain maps" to the narrative set about "protecting man-made structures" into a third narrative set, by reiterating the framing factors of each of the first two narrative sets and establishing them as foundational to determining where the wall should be built. Figure 6 is a graphical representation of the way the narrative sets in the example shown in Table 9 stand in relation to one another. As can be seen in the illustration, it is not necessarily the elaborating factors belonging to each narrative set that are connected individually to those of another set, but rather the broad ideas of the two sets containing elaborating factors are connected.

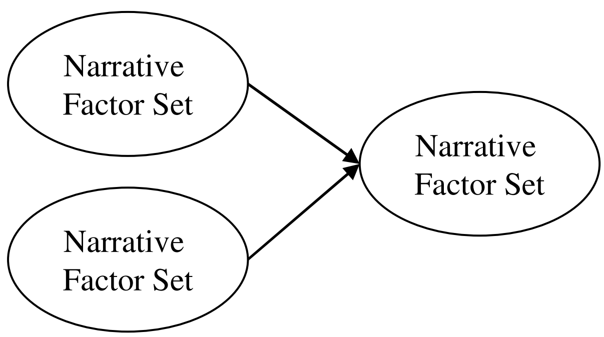

Figure 6. Two narrative sets are joined to contribute to a third.

Embedding a narrative set within another narrative set

Embedding one narrative set of related factors in another was another way experts connected their broad ideas. Peter exhibits this way of organizing his thoughts. Table 10 contains an abridged version of an instance where Peter embeds one narrative set of related factors in another.

Table 10. Embedding one narrative factor set in another.

Factor type	Narrative segment
FRAME 1	you just want to look at probabilities of exceeding certain flood heights,
ELAB 1	because maximum flood height needs to be defined
ELAB 1	defined as far as well as you're talking about a fifty-year flood, a hundred-year flood, a thousand-year flood.
ELAB 1	So, what, what I'm saying is it needs to be defined by recurrence interval.
FRAME 2	….Ok, we need to select the reasonable recurrence interval
ELAB 2	and that needs to be based on what are you protecting.

ELAB 2	…is it a hospital, police station, farmland?
ELAB 2	We would chose differently depending upon what we are actually trying to protect
ELAB 2	…because we don't want to waste a lot of money protecting something that is not of high value
FRAME 3	Ok, I would take into account the budget we have available…

The frame of the initial narrative factor set is "probabilities of exceeding certain flood heights." As Peter elaborated on the meaning of this broad factor, he came to the concept of the flood "reasonable recurrence interval." He then considered the kinds of factors that would influence a designer's determination of a reasonable recurrence interval. As he elaborated on this concept, he came to the concept of cost, and then proceeded to develop a narrative set of related factors framed by the concept of budget. Figure 7 contains a graphical illustration of the relationships among these narrative sets, as shown in the example in Table 10. As represented in the illustration, an elaborating factor from one narrative set subsequently becomes the framing factor for a new narrative set.

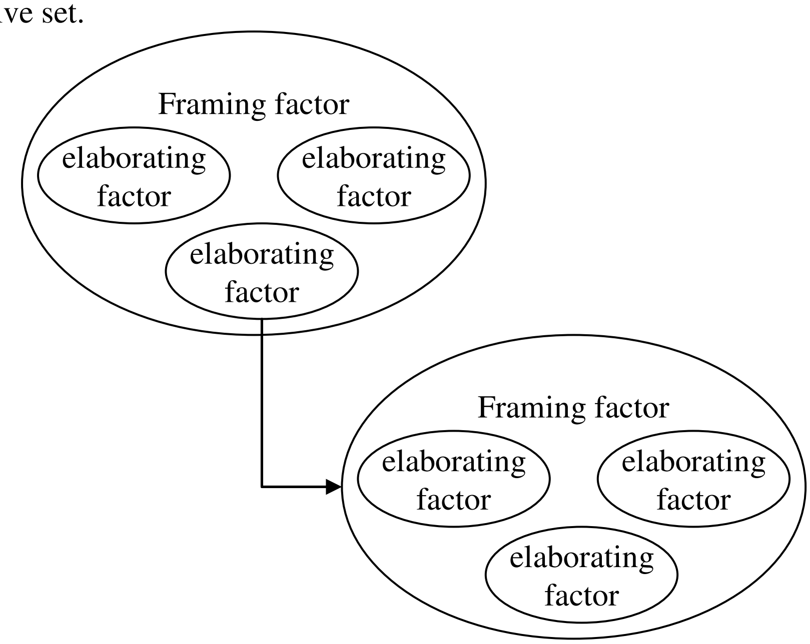

Figure 7. One narrative set of related factors embedded in another.

Discussion and Implications for Future Research

One advantage to concentrating on a small number of respondents is that the variation in design behavior from one expert to the next comes into clarity. The four experts exhibited little commonality with one another when analyzed using the VPA coding scheme for breadth of problem scoping. Two experts, Ann and Peter, provided relatively few statements to the MWF problem, while the other two experts, Eric and John, provided many. Furthermore, their statements were not distributed in similar ways across the four frame of reference categories or the four location categories. Eric's and John's focus was nearly evenly split between design detail and design context, while Ann's and Peter's focus on context was greater than their focus on detail. These findings may follow previous research that shows experts tend to take a top-down, breadth-first approach to design.[37] If the two experts who offered relatively few ideas statements about the MWF had engaged with it for a longer period of time, perhaps they would have shifted their focus more evenly toward the details of the design.

Because of the differences in data collection methods, we were unable to make direct comparisons between the expert responses and novice responses from the Academic Pathways Study. However, we were able to compare the distributions of their statements into the coded categories. We found that novices offered a greater proportion of factors from natural and social frames of reference, versus technical and logistical frames. This may reflect the novices' relative inexperience with engineering concepts; many of the freshmen in the Academic Pathways Study had not even taken any engineering design courses yet. Of course, greater numbers of experts with whom to compare should provide more interesting and meaningful results, and our next step with the VPA will be to segment and code the remaining transcripts from our expert sample.

The narrative analysis provided some promising directions for future research. First, it allowed us to identify particular kinds of factors that the four experts in our sample were drawn to -- existing engineered solutions, alternative design solutions, costs and benefits, priorities, and history. These types of factors stood out among others provided by experts as significant themes in their narratives and potentially different from what the novices had tended to highlight. We would like to revisit the novice data in the near future using a narrative lens to determine exactly how often and in what ways students considered these factors.

More interestingly, narrative analysis allowed us to see the relationships between and among an expert's ideas, and develop new understandings of what those relationships look like and how they reflect expert designers' thought processes. Further analyzing the transcripts for these four experts and including those of the other experts in the study, we should be able to identify additional ways of thinking about and doing engineering and affirm or elaborate on the narrative theories we have presented here. Illuminating the thought processes of expert designers can provide direction for improving the way we educate novices.

References

[1] Sheppard, S.D., "A Description of Engineering: An Essential Backdrop for Interpreting Engineering Education," *Proceedings (CD),Mudd Design Workshop IV*, Claremont, Cal.: Harvey Mudd College, 2003.

[2] Dym, C.L., Agogino, A.M., Eris, O., Frey, D.D., and Leifer, L.J. (2005). "Engineering design thinking, teaching, and learning." *Journal of Engineering Education 94*(1). 103-120.

[3] ABET (2006). "Criteria for Accrediting Engineering Programs," http://www.abet.org/forms.shtml, accessed November 29, 2006.

[4] Atman, C.J., Chimka, J.R., Bursic, K.M. & Nachtman, H. L. (1999). "A Comparison of Freshman and Senior Engineering Design Processes," *Design Studies*, 20(2), 131-152.

[5] National Academy of Engineering (2004). The Engineer of 2020. Washington, DC: The National Academies Press, p. 56.

[6] Shuman, L.J., Besterfield-Sacre, M., McGourty, J. (2005). “The ABET ‘Professional Skills’ -- Can they be taught? Can they be assessed?” *Journal of Engineering Education 94*(1). 41-55.

[7] Chubin, D.E., May, G.S., and Barco, E.L. (2005). “Diversifying the engineering workforce.” *Journal of Engineering Education 94*(1). 73-86.

[8] Bereiter, C & Scardamalia, M. (1993). *Surpassing ourselves: An inquiry into the nature and implications of expertise.* Chicago: Open Court.

[9] Chi, M. T. H. (2006). Two Approaches to the Study of Experts’ Characteristics. In Ericsson, K. A., Charness, N., Feltovich, P. J., & Hoffman, R. R. (Eds.). <u>The Cambridge handbook of expertise and expert performance.</u> New York: Cambridge University Press.

[10] Ericsson, K.A., & Smith, J. (1991). Prospects and limits of the empirical study of expertise: an introduction. In K. A. Ericsson & J. Smith (Eds.), *Toward a general theory of expertise*, pp.1-39. Cambridge, MA: Cambridge University Press.

[11] Cross, N. and Clayburn Cross, A. (1998). Expertise in engineering design. *Research in Engineering Design*. 10(3), pp. 141-149.

[12] Jain, V.K. and Sobek, D. K. II. (2006), "Linking Design Process to Customer Satisfaction Through Virtual Design of Experiments", *Research in Engineering Design*, 17(2), pp. 59-71.

[13] Bogusch, Laura L., Turns, Jennifer, and Atman, Cynthia J. (2000). “Engineering Design Factors: How Broadly Do Students Define Problems?”, *American Society of Engineering Education Frontiers in Education 2000 Conference Proceedings*, pp. 7-12.

[14] Rhone E, Turns J, Atman CJ, Adams R, Chen Y, Bogusch L (2001). “Analysis of Senior Follow-up Data: The Midwest Floods Problem-Addressing Redundancies in Coding” in CELT Technical Report #01-05,Center for Engineering Learning and Teaching, University of Washington, Seattle.

[15] Adams, Robin S., Jennifer Turns and Cynthia J. Atman. “Educating Effective Engineering Designers: The Role of Reflective Practice”, *Design Studies*, Special Issue on Designing in Context, vol. 24, no. 3, 2003. pp. 275-294.

[16] Kilgore, D., Atman, C.J., Yasuhara, K., and Barker, T. (2007). “Engineering Thinking and Doing in the First Year: Some Findings from the Academic Pathways Study,” Submitted for review to Journal of Engineering Education, February 2007.

[17] Christiaans, H. H. C. M. and Dorst, K. H. (1992). Cognitive models in industrial design engineering: A protocol study. *Design Theory and Methodology*. 42, pp. 131-140.

[18] Radcliffe, D. F. and Lee, T. Y. (1989). Design methods used by undergraduate engineering students. *Design Studies*. 10(4), Pp. 199-209

[19] Roberts, C., Henderson, M., Morrell, D., Grondin, B., Hinks, R., Kuo, C. Y., Sugar, T., and Yasar, S. "Exploring Freshman Engineering Design Teams: A Verbal Protocol Analysis Study Using I-PACE.” To appear in the

Proceedings of the Annual American Society of Engineering Education Conference, June 2007, Honolulu, Hawaii.

[20] Candy, L. and Edmonds, E. (1996). Creative design of the Lotus bicycle: implications for knowledge support systems research. *Design Studies*. (17), pp. 71-90.

[21] Cross, N., Christiaans, H., & Dorst, K. (1996). Analysing design activity. John Wiley & Sons.

[22] Ullman, D. G., Dietterich, T. G., and Stauffer, L. A. (1988). A model of the mechanical design process based on empirical data. AI EDAM. 12(1), pp. 33-52.

[23] Mosborg, Susan, Monica E. Cardella, Jason J. Saleem, Cynthia J. Atman, Robin S. Adams, and Jennifer Turns. (2006). 'Engineering Design Expertise Study', CELT Technical Report CELT-06-01, Center for Engineering Learning and Teaching, University of Washington, Seattle.

[24] Atman, C. J., Adams, R. S., Mosborg, S., Cardella, M. E., Turns, J., Saleem, J. "Engineering Design Processes: A Comparison of Students and Expert Practitioners", Submitted for review to Journal of Engineering Education, February 2007.

[25] Franzosi, Roberto. (1998). "Narrative Analysis--Why (and How) Sociologists Should be Interested in Narrative." In *The Annual Review of Sociology*, edited by John Hagan, 517-54. Palo Alto, CA: Annual Reviews.

[26] Ericsson, K. A,, & Simon, H. (1993). *Protocol analysis: Verbal reports* as *data*. Cambridge, MA: MIT Press.

[27] Cross, Nigel. (2001). "Design Cognition: Results From Protocol and Other Empirical Studies of Design Activity," In C. Eastman, W.M. McCracken and W.C. Newstetter (Eds.) *Design knowing and learning: Cognition in design education*. New York: Elsevier.

[28] Mullins, Carie A., Cynthia J. Atman, and Larry J. Shuman (1999), "Freshmen Engineers' Performance When Solving Design Problems," IEEE Transactions on Education, 42 (4), 281-287.

[29] Chi, M.T.H. (1997). "Quantifying qualitative analyses of verbal data: A practical guide, *The Journal of the Learning Sciences*, 6(3), pp. 271-315.

[30] Atman, Cynthia J. and Karen M. Bursic (1998), "Verbal Protocol Analysis as a Method to Document engineering Student Design Processes," Journal of Engineering Education 87 (2), 121-132.

[31] Bruner, Jerome (1996). The culture of education. Cambridge, MA: Harvard University Press

[32] Clandinin, D. J. and Connelly, F. M. (2004). Narrative inquiry: Experience and story in qualitative research. San Francisco: Jossey-Bass.

[33] Schon, Donald A. (1983). The reflective practitioner: How professionals think in action. New York: Basic Books.

[34] Creswell, J.W.; Clark, V.L.P.; Gutmann, M.L.; and Hanson, W.E. (2003). "Advanced Mixed Methods Research Designs." In *Handbook of Mixed Methods in Social and Behavioral Research* (A. Tashakkori and C. Teddlie, Eds.). Thousand Oaks, CA: Sage.

[35] Johnson, R.B. and Onwuegbuzie, A.J. (2004). "Mixed methods research: A research paradigm whose time has come." *Educational Researcher, 33*(7), pp. 14-26.

[36] Kilgore, D., Atman, C. J., Yasuhara, K., Barker, T. J., Morozov, A. "Considering Context: A Study of First-Year Engineering Students," Submitted for review to Journal of Engineering Education, February 2007.

[37] Ball, L.J.; Evans, J.S., Dennis, I, and Ormerod, T.C. (1997). Problem-solving strategies and expertise in engineering design. *Thinking and Reasoning 3*(4), pp. 247-270.

Author Biographies

ANDREW MOROZOV is a graduate student in Educational Psychology, College of Education, University of Washington. Andrew is working on research projects within the Center for Engineering Learning and Teaching (CELT) and the Center for the Advancement of Engineering Education (CAEE).

DEBORAH KILGORE is a Research Scientist in the Center for Engineering Learning and Teaching (CELT) and the Center for the Advancement of Engineering Education (CAEE), University of Washington. Her areas of specific interest and expertise include qualitative and mixed educational research methods, adult learning theory, student development, and women in education.

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). Dr. Atman is a Professor in Industrial Engineering. Her research focuses on design learning and engineering education.

Acknowledgements

This material is based on work supported by the National Science Foundation under Grant No. ESI-0227558, which funds the Center for the Advancement of Engineering Education (CAEE). CAEE is a collaboration of five partner universities: Colorado School of Mines, Howard University, Stanford University, University of Minnesota, and University of Washington. We would like to acknowledge the valuable contributions of colleagues on the leadership team of the Academic Pathways Study, Lorraine Fleming, Sheri Sheppard, Karl Smith, Reed Stevens, and Ruth Streveler. This work was also supported in part by National Science Foundation grants EEC-0639895 and REC-0125547. We would like to gratefully acknowledge the students who participated in the study, and the students who helped us to code the protocols, specifically Elvia Karina Sierra-Badillo, Adrienne Oda, and Ngoc Bao Nguyen. We would also like to thank Theresa Barker, who led the coding effort of the student data, and Robin Adams and Jennifer Turns who were co-Principal Investigators with Cindy Atman on the grant that funded the collection of the expert data. Finally, we would like to thank our Engineering Thinking and Doing colleagues Jason Saleem and Ken Yasuhara for their insightful help with this work.