An Application of Protocol Analysis to the Engineering Design Process[1]

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Abstract

The objective of this paper is to demonstrate verbal protocol analysis as a method to document and analyze how students approach open-ended engineering design problems. As part of a larger effort to study how engineering students solve design problems, freshmen and senior engineering students were asked to design a playground for a fictional neighborhood. This paper will demonstrate the use of the verbal protocol method as shown by an in-depth analysis of one of the subjects from this study. The type of data that can be obtained and the various questions that can be answered using verbal protocol analysis will be discussed. This research methodology can be a very valuable tool to assess how engineering students approach open-ended design problems. This information is vital to engineering faculty who must teach the design process to freshmen.

Introduction

Design is a key element of the engineering discipline. In recent years there have been numerous calls for improvement in engineering education, including the teaching of design. Industry and academic panels, university coalitions, and individual researchers have studied engineering education curricula and made many recommendations for engineering educators [(1-4)]. As a result, undergraduate engineering education in the United States has undergone many changes in response to criticism about the ability of graduating engineers to succeed in the "real world". As part of these changes, many engineering schools are introducing design early in a student's curriculum - as early as the freshmen year [(5-7)]. A review of the proceedings from the 1995 American Society for Engineering Education (ASEE) Conference (Anaheim, CA; June, 1995) and the IEEE and ASEE jointly sponsored Frontiers in Education Conference (Atlanta, GA; November, 1995) confirms that changes are well underway.

Before we can fully develop and implement more effective strategies to teach design, it is vital that we understand how students approach open-ended engineering design problems. Assessment of how engineers solve problems is a challenging task. This type of analysis can be very difficult and time consuming. One research method, known as verbal protocol analysis, is particularly useful for accomplishing this type of task.

Verbal protocol analysis requires subjects to think aloud as they perform a task while being audio and/or video treed. Tapes are then transcribed, segmented, coded, and analyzed. Segmenting involves dividing the transcripts into codable units of texts. Coding usually requires a pre-defined coding scheme. This method provides a systematic way to analyze the content of what a subject says as he or she performs a task[(8)].

Verbal protocol analysis has been used extensively in research on learning. It has also been used in reading research to gain insight into what a reader understands from written text [(9)]. Ericsson and Simon

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demonstrate the validity of the method and argue that concurrent reports area valid method to obtain data about thinking processes[10]. They also argue that, if done properly, think-aloud procedures do not influence the sequence of thoughts of subjects and that the resulting data can be treated as objectively as any other data. Information is collected from short-term memory while subjects are prompted to "keep talking" with minimal interference from the experimenter. In the analysis of the resulting data (the "protocol"), a coding scheme that requires minimal coder interpretation and inference is required to maintain the reliability of the data.

Several studies have used verbal protocol analysis to describe designers' (both novices and experts) processes in detail. For example, Christians andDorst(11, conducted a study to explore the *role* of knowledge in industrial design engineering. Sutcliffe and Maiden [12] studied novice systems analysts in a requirements task using protocol analysis. Guindon [13] studied experienced software designers to determine whether top-down decomposition of a problem is effective in the early stages of design. Ennis and Gyeszly [14] studied six experienced and successful designers solving engineering packaging problems. Verbal protocol analysis was used to identify how the designers introduced information or knowledge into the design process. Thus, several in-depth studies have been done to analyze how various levels of engineers, analysts, and designers approach and solve open-ended design problems. Using verbal protocol analysis, Atman and Bursic [15] found that student performance in solving open-ended engineering design problems was positively affected by reading a design text. However, more research needs to be done on *student approaches* to open-ended engineering design problems. This information can help us develop an understanding about more effective teaching methods.

The study described here is part of a larger research effort in which the goal is to understand how engineering students approach open-ended design problems. The objective of the larger study is to document student problem solving processes by obtaining detailed descriptions of those processes. In this paper, we show how this objective is obtained by demonstrating the usefulness of verbal protocol analysis through a detailed application of the method to one subject in our study.

The Experiment

In this study, students were asked to give a verbal protocol as they solved a playground design problem. This problem is a revised version of a term-long design project used by the University of Maryland (part of the National Science Foundation's ECSEL coalition)[5]. The text of the problem is presented in Figure 1.

The experimental procedure consisted of several steps. First, subjects solved two practice problems out loud to familiarize themselves with the process of thinking aloud. They were then given the playground problem and asked to read it out loud. Subjects were given up to three hours to complete the problem and were encouraged to request information regarding the problem from the experiment administrator at any time during the three hours. Each subject gave a verbal protocol while they solved the problem. If the subject fell silent during the protocol, the experiment administrator prompted the individual to keep talking. Once a subject completed the playground problem, he or she read a one page description of the design process. Subjects were also asked to comment on their performance with respect to this description and provide demographic information about themselves. Both audio and video tapes were used to collect subject protocols.

The subjects used for this study included 26 freshmen engineering students and 24 senior engineering students at the University of Pittsburgh. The freshmen students participated in the study just prior to the start of their first semester or a few weeks into the semester, before any design concepts were covered in the freshmen Introduction to Engineering course. Seniors participated while they were in their last semester of school. Each student was paid thirty dollars for their time.

Designing A Playground

You live in a mid-size city. A local resident has recently donated a comer lot for a playground. Since you are an engineer vho lives in the neighborhood, you have been asked by the city to design a playground.

You estimate that most of the children who will use the playground will range from 1 to 10 years of age. Twelve children hould be kept busy at any one time. There should be at least three different types of activities for the children. Any equipment you lesign must:

- be safe for the children
- remain outside all year long
- not cost too much
- comply with the Americans with Disabilities Act.

The neighborhood does not have the time or money to buy ready made pieces of equipment. Your design should use material: hat are available at any hardware or lumber store. The playground must be ready for use in 2 months.

Please explain your solution as clearly and completely as possible. Someone should be able to build the playground from 'our solution without any questions. The administrator has a lot more information to help you address this problem if you need it. 3e as specific as possible in your requests.

For example, if you would like a diagram of the comer lot, some information about the lot appearance, etc., you may ask for t now. If you think of any more information you need as you solve the problem, please ask for it.

Remember, you have approximately 3 hours to develop a complete solution. The administrator will tell you how much time s left while you work.

'igure 1: Student Instructions for the Playground Design Problem

An Application of Verbal Protocol Analysis

To demonstrate the use of verbal protocol analysis, we selected one female subject whose protocol we believe represents the typical freshman subject. The subject's verbal protocol was transcribed from audio tapes to form the "data" for the analysis. The transcript was then segmented, coded, and analyzed. Each of these processes are described in the following sections.

Segmenting

Segmenting is the process of breaking the verbal text into units (or segments) that can be coded with a predefine coding scheme. A sentence forms the basic segment to be coded for these protocols. In our study, if a sentence contained more than one idea, it was segmented into more parts. The segmenting was done by two analysts and checked for reliability. Reliability was found by dividing the total number of discrepancies (or disagreements between coders) by the total number of segments in the transcript. Reliability scores for the segmenting process in this study have been consistently greater than .90. Figure 2 shows a portion of the protocol from the sample subject. The top portion of the figure shows the original transcript and the lower portion shows the transcript segmented into codable units of text. Once the segmenting was complete, the transcript was imported into Mac SHAPA[16], a software tool that assists with analysis of verbal data. MacSHAPA creates a spreadsheet that includes the segmented verbal text as the first variable (or column). Each segment is represented as a cell (or row) in the spreadsheet.

original Transcript	This, this support which will cost five-sixty will be... divided by two, two poles, hmmm, zero twelve carry the one eleven dollars and twenty cents for the two cost of supports, the longer supports, the bottom be two inches long, two feet long, ah, two and a half feet diameter, at a dollar twelve, (pause) two feet long at dollar twelve, that's four feet, four feet four, four forty-eight total cost of this. ..total support cost would be. ..four forty-eight... six five fifteen dollars sixty-eight cents, hmmm...hmmm, two of the walls, so that fourteen foot wide times two four six eight eight dollars sixty-four cents plus twenty-four... dollar six (said very quietly) total, [inaudible comment] thirty-two dollars... sixty-four cents, hmmm, thirty-two sixty-four plus fifteen sixty-eight total of one seventeen times three-eights brings.. forty-eight thirty-two for the smaller slide.
Segmented Transcript	This, this support which will cost five-sixty will be... divided by two, two poles, hmmm, zero twelve carry the one eleven dollars and twenty cents for the two cost of supports, the longer Supp orts,
	the bottom be two inches long, two feet long, ah, two and a half feet diameter, at a dollar twelve, (pause) two feet long at dollar twelve, that's four feet, four feet four, four forty-eight total cost of this.
	total support cost would be.. four forty-eight. ..six five fifteen dollars sixty-eight cents, hmmm...hmmm,
	two of the walls, so that fourteen foot wide times two four six eight eight dollars sixty-four cents plus twenty-four... dollar six total, [inaudible comment] thirty-two dollars... sixty-four cents, hmmm, thirty-two sixty-four plus fifteen sixty-eight total of one seventeen times three-eights brings.. forty-eight thirty-two for the smaller slide.

Figure 2: Sample Portion of Subject's Protocol

Coding

Four variables were used to describe the student's problem solving process. These are shown in the resulting coding scheme in Table 1. The first variable, *"step"* identifies the step in the design process that is represented by that segment of the protocol. These steps were identified through a content analysis of seven freshmen engineering design texts[17]. The second variable, *"information processed"*, identifies what information the subject is addressing for that segment. For example, the subject maybe addressing the BUDGET, MATERIAL COSTS, or SAFETY. This variable includes a wide range of codes from technical information to more practical issues such as handicapped accessibility. The third variable, called *"activity"*, is used to identify what the subject is doing such as READING or CALCULATING. Finally, *"object"*, identifies what equipment the subject is working on, for example: SWINGS, SEE-SAW, WATER FOUNTAIN, EQUIPMENT, etc. In the table, we have only shown a sample of the *information processed*, *activity*, and *object* codes.

Two coders separately assign one of the codes to each segment in the subject's protocol for each of these four variables. Coders then check their codes to see if they match, and come to consensus on any discrepancies. Reliability is determined by the total number of discrepancies (before consensus) divided by the total number of subject's segments in the transcript (experimenter comments are not coded). The coding scheme was refined until coders were able to consistently obtain reliability scores of .90 or better.

Table 2 shows three portions of the sample subject's transcript and the appropriate coding for each. The first portion is representative of the early stages of the subject's design. The subject was doing problem scoping (which might include identifying a need, defining the problem, or gathering information) and interacting with the experimenter to obtain information. For example, in segment number 38 the design *step* was coded GATHER INFORMATION since the subject was inquiring about types of materials. *Information processed was* therefore coded MATERIALS. *Activity* was left BLANK because none of the codes apply. Likewise, *object* was left BLANK since the subject was not working on any equipment at this stage of the design. The second portion

Variable	Code	Symbol	Description
Step	NEED	N	**Identify** basic needs (purpose, reason for design).
	PROBLEM DEFINITION	PD	**Define** what the problem really is, identify constraints, identify **criteria,** reread [problem statement **or information sheets** for **a second or third time,** question the **problem** statement.
	GATHER INFORMATION	GATH	**Searching** and collecting needed information, asking for and reading information from the experimenter.
	GENERATE IDEAS	**GEN**	Develop possible ideas for a solution, brainstorm, come up with ideas, list different alternatives.
	ANALYSIS MODELING	**AM**	Modeling, describe how to build the idea, how to make it, measurements, **dimensions,** calculations.
	ANALYSIS WORKABILITY	**AW**	Determining **workability,** verification of **workability,** does it meet **constraints,** criteria, does it make sense, etc.
	EVALUATION	**EVAL**	Comparing alternatives, judgment about various options, is one better, cheaper, more accurate.
	DECISION	DEC	**Select** one idea or solution **among** alternatives.
	COMMUNICATION	COM	**Define** the design to others, write down a solution or instructions.
Information **Processed***	**BUDGET**	BUD	preference to the amount of money available to build the equipment or to the total **cost** of **a particular piece of equipment.**
	MATERIALS	**MAT**	Any *general* reference to the type or kind of material needed (wood, steel, etc.)
	MATERIAL COSTS	**MC**	Costs for all building materials, benches, and plants.
	DIMENSIONS	'DIM	Dimensions for any piece of equipment or part of the layout.
	MATERIAL SPECIFICATIONS	MAT SPEC	Any references made to building codes and the strengths of materials to be used, references to engineering **properties.**
	NEIGHBORHOOD AREA	NA	The locations of nearest bus stop, school, river, forest, hospital, police station, **fire** department, factory, homeless shelter, and other similar parks.
	PARK AREA	PA	**Layout** of the **park,** description of the lot.
	SAFETY	**SAF**	**All safety** guidelines and any considerations made by the subject.
	HANDICAPPED ACCESSIBILITY	HA	**Reference** to making equipment more accessible for all types of handicapped **children.**
	OUTSIDE	OUTSD	**Ensuring equipment** csn remain outside all vear **long.**
	OTHER	O	**Anything** else **that** should be noted.
Activity *	READ/REREAD	R	**Reading** or rereading the problem statement or other information.
	CALCULATE	CAL	**Doing** cost. **dimensions.** or other **types** of calculations.
	EXPLICIT ASSUME	EA	**Making** explicit assumptions.
	IMPLICIT ASSUME	IA	**Making implicit assumptions.**
	CONSTRAINTS	CON	When a subject **identifies,** deals with, or checks to scc if a constraint is met.
	INFORMATION REQUEST UNAVAILABLE	IRU	Subject requested something which the experimenter could not give.
Object *	SLIDE	SLIDE	Small or large slide.
	WOOD STRUCTURE	WOOD STRUCT	Wooden jungle gym **structure.**
	STEPS	STEPS	Steps for the structure.
	SWING	SWING	**Small** or lame **swing.**
	LANDSCAPING	LNDSCP	**Trees,** bushes, flower, or any aesthetics for the park.
	EQUIPMENT	**EOUIP**	**General** term for **working** on more than one activitv at a time.
	LAYOUT	LAYOUT	Working on where to put the different activities in the park.
All Variables	BLANK	BLANK	**Inserted** when no codes apply to the cell.

*Indicates a partial list of the codes for that variable

Table 1: Coding Scheme

shown is representative of the largest part of this subject's protocol, analysis. Clearly, in this section she was focused on doing technical calculations. This is demonstrated by segment number 113 where *step was* coded ANALYSIS - MODELING, *information processed* was coded MATERIAL COSTS, *activity was* CALCULATE, and the *object* was a SLIDE. In the last portion of the protocol shown, the subject reread the problem statement. She then determined whether her solution met the problem constraints. This is indicated in segment 347 by the codes PROBLEM DEFINITION, SAFETY, and CONSTRAINT.

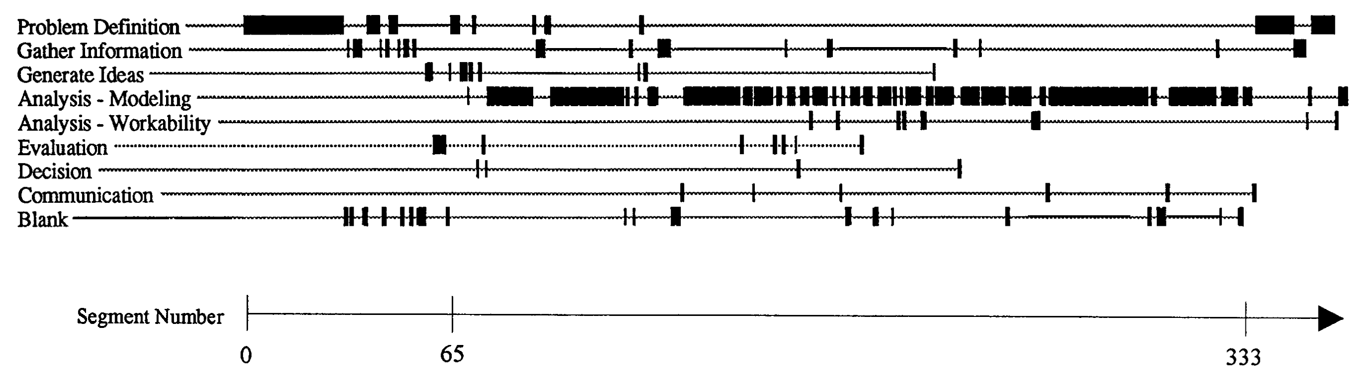
Design Stage	Seg. #	Segment Text	step	Information Processed	Activity	Object
Problem Scoping	38	Hmmm do you have, a list of materials at the...from the hardware store or do I have to think of that?	GATH	MAT	BLANK	BLANK
	39	Ok. Hmmm, lumber?	GATH	MAT	BLANK	BLANK
	40	1 have to have all the materials, everything I'm gonna need?	GATH	MAT	BLANK	BLANK
	41-42	Ok. Ok. Ok.	BLANK	BLANK	BLANK	BLANK
	43-46	And the corner lot is perfectly flat... (Student Reading) . . . One gate faces Second Avenue and the other faces Pine Street.	PD	PA	R	BLANK
	47	Hmmm, can I ask you for hmmm, sane kind of a something to clear the lawn with.. a tractor or a...	GATH	o	IRU	BLANK
Analysis	113	This, this support which will cost five-sixty will be...divided by two, two poles, hmmm, zero twelve carry the one eleven dollars and twenty cents for the two cost of supports, the larger supports,	AM	MC	CAL	SLIDE
	114	the bottom be two inches long, two feet long, ah, two and a half feet diameter, at a dollar twelve, (pause) two feet long at dollar twelve, that's fous feet, four feet four, four forty-eight total cost of this.	AM	MC	CAL	SLIDE
	115	total support cost would be...four forty-eight...six five fifteen dollars sixty-eight cents, hmmm...hmmm,	AM	MC	CAL	SLIDE
	116	two of the walls, so tbst fourteen foot wide times two four six eight eight dollars sixty-four cents plus twenty- four...dollar six total, [inaudible comment] thirty-two dollars...sixty- four cents, hmmm,thirty-two sixty -four plus fifteen sixty-eight total of one seventeen times three-eights brings.. fcrty-eight thirty-two for the smaller slide	AM	BUD	CAL	SLIDE
Check Constraints	347	[Inaudible] Any equipment you design must be safe for the children,	PD	SAF	CON	BLANK
	348	remain outside all year long	PD	OUTSD	CON	BLANK
	349	net cost too much	PD	BUD	CON	BLANK
	350	comply with the American with Disabilities Acl	PD	HA	CON	BLANK
	351	Do you have a copy of the Americans with Disabilities Act?	GATH	HA	CON	BLANK
	352-354	The Americans with Disabilities Act of 1990 . . . (Student rending) . . . An effort should be made to allow handicapped children to be able lo use the playground.	GATH	BLANK	R	BLANK
	355	Hmmm....my structure is wide enough . . . I think tire . . . think it would fit this plank is a good thing for than,	AW	HA	CON	WOOD STRUCT

Table 2: Sample ***Coded Segments***

Analysis of the Verbal Protocol

Once the coding is complete, a variety of questions can be answered from the coded protocols. For our study, these will be discussed in the context of each of the four variables coded.

Design Step. This variable can show us how a subject approaches the design problem. We can then compare this approach to a prescriptive model of the design process. For example, we can see if a subject proceeds with a linear path through the steps in the design processor whether they iterate through the steps as they develop and refine ideas. This variable also indicates the amount of effort each subject spends on the various steps of the design process. This will allow us to make comparisons between various subject groups (i.e. between freshmen and seniors or between students and experts). Figure 3 shows a timeline that represents the behavior of the sample subject across time with respect to the design process *step* variable. Time proceeds from left to right in the diagram. Each block in the figure represents a coded segment (or cell) from the subject's transcript. Regardless of the number of words contained, each cell is represented as the same size in the figure. All the subjects start by reading the problem, which is coded as PROBLEM DEFINITION. As a subject



Design Stage	Problem Scoping	Analysis	Checking Constraints
Segments Devoted	16% (65)	75% (268)	9% (35)
Information Processed	Materials (7) Park Area (5)	Dimensions (68) Materials (65) Material Cost (62) Budget (15)	Park Area (4) Hndcp. Access (3) Materials (3)
Activity	Read (25) Constraints (3)	Calculations (111) Constraints (18) Read (5)	Constraints (15) Read (12)
Object	Slide (2)	Slide (86) Wood Structure (56) Swing (32) Steps (14)	Equipment (2)

Figure 3: Subject's Progression Through the Design Process

(number in parentheses indicates number of segments coded as specified) progresses to other steps in the design process, a block is added in the diagram and labeled accordingly. The process is repeated to construct a diagram that represents all the stages in the design process a subject includes in their process as well as the order in which they visit each stage. Note that the codes NEED and IMPLEMENTATION are never used. This is because the need has already been identified for the subject in the problem statement and implementation was not a requirement in the experimental setting. This subject spent approximately 2 hours and 45 minutes working on the playground problem. The figure certainly indicates that she spent the majority of that time in the analysis stage of her design process (75% of the segments). Only 16% of the subject's segments were focused on problem scoping and 9% on re-checking constraints in the latter stages of her design process.

Figure 3 also shows how the other three variables are emphasized during the three major phases of the subject's design process. Under each phase, codes with the largest number of segments devoted to them are identified. For example, in the analysis phase the primary information processed was coded DIMENSIONS, MATERIALS, MATERIAL COSTS, and BUDGET.

Information Processed. This variable describes what specific information the subject is thinking about while they solve the problem. Figure 3 shows that this subject spent little effort on non-technical issues such as HANDICAPPED ACCESSIBILITY or SAFETY. She focused problem solving efforts almost exclusively on DIMENSIONS and MATERIAL COSTS.

Activity. The activity variable defines what the subject is doing at a particular point in his or her design process (e.g. reading the problem statement, performing calculations, making an assumption, etc.) From this we can determine: Does the subject identified and addressed all of the constraints outlined in the problem definition? How much time is the subject devoting to rereading the problem definition and information sheets? How much time does the subject devote to calculations? What assumptions did the subject make in solving the problem? Does the subject add anything unique or creative to his or her design? The sample subject's primary activity was performing CALCULATIONS, although she did attend to CONSTRAINTS throughout her design process.

Object. The *object* variable identifies what the subject is designing. The primary purpose of the *object* variable is to indicate how the subject moves from one object (or piece of equipment in the playground) to the next. To determine this, we can display a timeline that shows the flow across time from object to object similar to the timeline used to demonstrate the design *step* variable. Our sample subject spent time working on a variety of objects including a SLIDE, WOOD STRUCTURE, and SWING.

Discussion

Each of the variables that we have defined in this study can provide insight into student approaches to open-ended design problems. For example, the data from the sample protocol show that this subject spent the majority of her effort performing calculations to design specific equipment. She primarily processed information on materials, dimensions, and material costs. She spent little effort on problem scoping and did not consider many non-technical issues such as handicapped accessibility, the neighborhood, or safety. In fact, she only asked for a copy of the Americans with Disabilities Act (ADA) during the final stage of her design process and gave a brief evaluation of her design with respect to the ADA. Little effort was placed on evaluating her final design. The analysis of this subject's protocol demonstrates how verbal protocol analysis allows us to determine what a subject believes is important for solving a design problem. This can be done by evaluating the amount of effort a subject spends in a particular area (with respect to any of the four variables).

This method provides a variety of data for analysis. For example, we compared the types of information students requested when solving open-ended problems(18). This enabled us to understand the scope of information students felt was important in solving the problem. That is: What information do they consider in their design? Do they consider only engineering and technical information or do they expand the problem scope to include contextual issues such as information on safety, the neighborhood, and the surrounding area? We can also obtain data on the occurrences of a number of activities such as reading, calculating, making assumptions, meeting constraints, and self-assessment of task performance. Do students take a sequential approach in their design or do they iterate frequently through the design process steps? Do they spend enough time in problem definition or do they go directly to analysis and evaluation?

Verbal protocol analysis is a powerful tool for understanding the design process. Analysis of the verbal protocol enables us to look at a subject's process in detail rather than simply "grading" a final solution. That is, we can now grade the "process" as well as the final design. In essence, it provides us with a measure that can be used to assess student process skills. We can also rate the quality of the subjects playground designs. By measuring both the "product" and the "process", we can explore whether a relationship exists between the type of process a student uses and the quality of the final design. Knowing this relationship, we can then distinguish between good and poor processes and indicate specific problems that must be addressed as we teach design.

In conclusion, we have found that verbal protocol analysis is a useful tool for documenting student approaches to open-ended engineering design problems. It can help us determine what students feel is most important in solving these problems and where they spend most of their time. The next step in this research project is to conduct a similar analysis with all of the data so that we can make comparisons between freshmen and senior subjects. When we examine the data from the senior students and compare this data to the freshmen protocols, we will be able to determine what students have learned about design in the four year curriculum. Ultimately, we hope to use this method to evaluate various design teaching methods. This will provide the engineering education community with information useful to guide changes in the classroom.

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References

1 Bordogna, Joseph, Eli Fromm and Edward W. Ernst, "Engineering Education: Innovation Through Integration," Journal of Engineering Education, v. 82, n. 1, January, 1993, pp. 3-8.

2 "Engineering Education for a Changing World," Report from the Engineering Deans Council and Corporate Roundtable of the American Society for Engineering Education, October, 1994.

3 National Research Council, Engineering Education: Designing an Adaptive System, National Academy Press, Washington, D. C., 1995.

4 National Science Foundation, Restructuring Engineering Education: A Focus on Change, Division of Undergraduate Education, Directorate for Education and Human Resources, 1995.

5 Dally, J. W., and G. M. Zhang, "A Freshman Engineering Design Course," Journal of Engineering Education, v. 82, n. 2, April, 1993, pp. 83-91.

6 Dym, Clive L., "Teaching Design to Freshmen: Style and Content," Journal of Engineering Education, v. 83, n. 4, October, 1994, pp. 303-310.

7 McConnell, R. L., Wallace Venable, and Alfred Stiller, "Freshmen Can Do Rigorous Open-Ended Design, " 1995 Frontiers in Education Conference Proceedings, IEEE, Inc., pp. 3C4. 1- 3C4.4

8 Chi, Michelene, T. H., "Analyzing the Content of Verbal Data to Represent Knowledge: A Practical Guide," Submitted to Journal of the Learning Sciences, June, 1994.

9 Schriver, Karen A., "Evaluating Text Quality: The Continuum from Text-Focused to Reader-Focused Methods," IEEE Transactions in Professional Communication, v. 32, n. 4, 1989, pp. 238-255.

10 Ericsson, K. Anders and Herbert A. Simon, Protocol Analysis: Verbal Reports as Data, The MIT Press, Cambridge, Massachusetts, 1993.

11 Christians, Henri H. C.M., and Kees H. Dorst, "Cognitive Models in Industrial Design Engineering: A Protocol Study," Design Theory and Methodology , v. 42, American Society of Mechanical Engineers, 1992.

12 Sutcliffe, A. G. and Maiden, N. A. M. "Analysing the Novice Analyst: Cognitive Models in Software Engineering," International Journal of Man-Machine Studies, V. 36, 1992, pp. 719-740.

13 Guindon, Raymond, "Designing the Design Process: Exploiting Opportunistic Thoughts," Human-Computer Interaction, v. 5, 1990, pp. 305-344.

14 Ennis, Charles W. Jr., and Steven W. Gyeszly, "Protocol Analysis of the Engineering Systems Design Process," Research in Engineering Design, v. 3, 1991, pp. 15-22.

15 Atman, Cynthia J. and Karen M. Bursic, "Teaching Engineering Design: Can Reading a Textbook Make a Difference?" submitted to Research in Engineering Design, January, 1995.

16 Sanderson, Penelope M., MacSHAPA Reference Manual, University of Illinois at Urbana-Champaign, Urbana, IL, Distributed by Crew System Ergonomics Information Analysis Center, 1994.

17 Moore, Pamela L., Cynthia J. Atman, Karen M. Bursic, Larry J. Shuman, and Byron S. Gottfried, "Do Freshmen Design Texts Adequately Define the Engineering Design Process?" ASEE Annual Conference Proceedings, 1995, pp. 164-171.

18 Atrnan, Cynthia J., Karen M. Bursic and Stefanie L. Lozito, "Gathering Information: What Do Students Do?" American-Society for Engineering Education Conference Proceedings, June, 1995, pp. 1138-1144.

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