AC 2007-262: COMMUNICATION AS A PROXY MEASURE FOR STUDENT "DESIGN ABILITY" IN CAPSTONE DESIGN COURSES

Alan Cheville, Oklahoma State University

Christine Co, Oklahoma State University

Christine Co is a fifth year senior in the Electrical and Computer program at Oklahoma State University who is receiving her BSEE in December, 2006. In 2007 she plans to fulfill her lifelong interest by attending medical school to become an opthamologist where she can combine her medical training with her undergraduate engineering degree. Christine would like to thank the National Science Foundation for supporting a summer REU fellowship in engineering education.

Bear Turner, Oklahoma State University

Darren "Bear" Turner is currently a senior in the School of Electrical and Computer Engineering at Oklahoma State University. Bear will graduate in December, 2006 with a BSEE degree and plans to move to a position in industry. Bear acknowledges support of the National Science Foundation Research Experience for Undergraduates program.

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Background and Context

Many engineering departments use capstone design courses in the undergraduate program in which students design, build, and test a complex project. These programs are increasingly industry sponsored [1], and expose students to many of the real constraints engineers face. Capstone courses are the primary mechanism used by many universities for integrating communication, and teamwork skills and social, economic, and ethical issues into the engineering curriculum [2]. The capstone concept has been extended by other schools such as the Design4Practice program at Northern Arizona University and the projects program at Worcester Polytechnic Institute [3-5] in which dedicated design courses are integrated into all four years of the undergraduate curriculum. Improvements in student performance following capstone programs have been observed in several studies [6], and capstone experiences are reported positively by graduates [2]. Capstone courses tend to focus on projects which are specific and unique, and many programs use capstone courses to cover multiple ABET outcomes that are not fully addressed elsewhere in the curriculum [1]. As a result, there is no widely accepted model or textbook on which capstone courses are based [7, 8]. The uniqueness of capstone courses, breadth of material covered, and the lack of a way to accurately to measure "design ability" makes it difficult to assess learning outcomes. A national survey [7] indicates that most capstone courses outcomes are broad, poorly defined, or the outcomes may vary between projects within a course. The difficulty of assessing outcomes for individual students is increased since most capstone courses are team-based and students may have very different roles or even be in different departments.

The electrical engineering department at Oklahoma State University uses a two course capstone design sequence. The first course teaches skills required for design, while the second course has teams tackle open-ended design projects. The format of both courses is representative of capstone courses at other universities as determined by the overlap of structure, outcomes, and grading methods with other capstone course nationwide [1].

This paper addresses student learning in the first capstone course which prepares students for open ended, team-based design projects in the second course. Although the primary goal of this course is improving student's engineering "design ability", it has proven difficult to measure changes due to a lack of measures of student learning that are good proxies for the multiple skills and characteristics that define "design ability". This paper introduces three simple measures of design ability that are based on a socio-constructivist framework. In order to determine if the measures developed can be broadly used in design courses we determine how they are correlated with student characteristics or attributes that are hypothesized to support design.

The preparatory capstone course uses a cognitive apprentice model [9] to teach students the engineering design process. The design process is taught in three consecutive steps:

- The first step provides students specific skills in electronic simulation, fabrication, or test and measurement. Students are taught skills by an expert (teaching assistant) then complete a small project which is evaluated by the expert. Students then use the acquired skills to contribute to a team project.

- The second step has each team design, fabricate, and test an electronic system; the systems designed by each team form different subsystems of a complex electronic system. While student teams are responsible for their designs, the design *process* is modeled by experts and coaching is provided for students.
- The third step is for teams to integrate each of the subsystems from the second step into a working system.

Each step uses the cognitive apprentice model. Design projects are scaffolded by ninety minutes per week of active learning instruction in the classroom.

In order to measure changes in student's design ability sub-outcomes that support design were drawn from published definitions of "engineering design" from ABET criteria or textbooks [10, 11]. The course sub-outcomes include:

- Being able to function on a team.
- Being able to design a system to meet a specific need.
- Acquiring individual skills to contribute to team projects.
- Developing engineering discernment [12].
- Being able to communicate technical results in writing.
- Basics of time and resource management.

While each of these outcomes can be taught and, in some cases, measured separately, successful team-based design requires the *integration* of multiple outcomes or domains of knowledge. Being capable or testing well in individual domains does not necessarily mean multiple domains can be integrated to confer design ability.

To measure overall "design ability" we propose that the ability to formally communicate both the process and details of design serves as a simple and valid proxy measure of overall ability in engineering design. Survey data indicates that the majority of capstone programs use evaluation of communication as the primary method of assessing outcomes. Such assessments tend to be subjective [7] and since most reports or presentations are done as a team, it can be difficult to determine the contributions or abilities of individual students. Previous work on evaluating communication in capstone design courses includes latent semantic analysis of team documents and e-mails. This work showed coherence of communication was positively correlated with better performance on design projects [13]. Verbal communication has previously been used as an assessment of a student's design process knowledge [14], however verbal protocol analysis is extremely time consuming for faculty. Rubric-based evaluation of student communication is relatively common, but as mentioned previously it can be difficult to extract contributions of individual students [15]. Confounding effects may also occur due to plagiarism given the relative high rate of academic dishonesty among engineering students [16].

This paper reports on three measures of design ability that can be given in addition to written team reports. The first measure is a "block diagram test" given to individual students in which they are asked to describe their design project through an engineering block diagram. The second measure is a team oral report focusing on different stages of the socio-constructivist learning cycle in which teams present the details of their project to other students. Oral reports are rated using a rubric by both teaching assistants and other students in the class. The third metric is a comparison between individual students' evaluations of other teams' reports to the scores given by experts (TA's).

Conceptual Framework

In order to model the process by which students learn engineering design, this research adopts a socio-constructivist framework [17]. Socio-constructivist theory as described by Vygotsky [18] asserts that individuals learn complex processes through a cyclical process. This cyclical process has been further interpreted by Harré [19] and is shown in Figure 1 as interpreted for engineering design. The *display* axis determines whether learning occurs in a public or private setting while the *realization* axis determines if the learning is driven by a collective understanding or work by an individual.

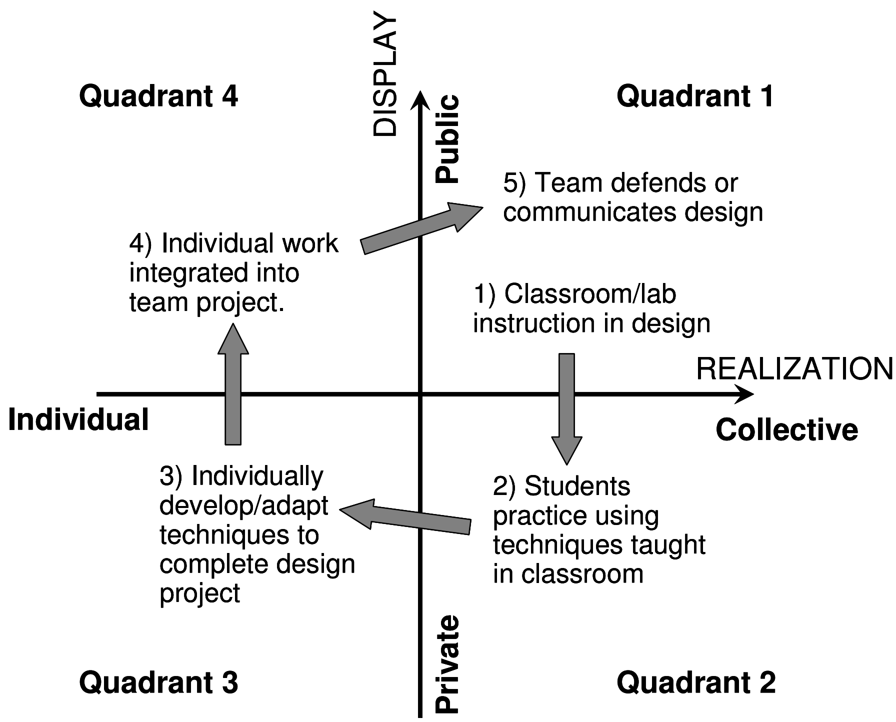

Figure 1: Harre's [19] interpretation of socio-constructivist learning as interpreted in learning the engineering design process in a capstone design course.

The socio-constructivist framework adopted in this work both models the learning processes which occur in capstone design courses and guides analysis of a student's ability to communicate the process of engineering design. In this framework the design process is completed in five steps:

1) A student's initial learning occurs through interactions with the faculty and teaching assistants (experts) in a social setting- the design class or lab. This type of learning is collective and public and represented by Quadrant #1. Students first seek to understand the design process and their project through social interactions in the classroom, laboratory, or within a team.

2) Next the team analyzes the design project and breaks it down to component tasks. At this stage students become individually responsible for particular portions of the project. This step is represented by Quadrant #2 where students begin to work individually on

their portion of the project. Their understanding of the design project and process is still general since it was determined by social interactions with the team and/or instructor.

3) In order to make an individual contribution to the team effort the student must master a portion of the design project by internalizing the design process and adapting their personal skills and knowledge to the task. In Quadrant #3 the learning cycle advances through internalization and individual practice; the student appropriates knowledge for their own use.

4) Finally, in Quadrant #4 the cycle concludes as the learner becomes a teacher and uses the knowledge of their portion of the design process in a social team setting to contribute to the group's success. The student integrates their work with that of the group.

5) Most capstone courses then "close the loop" by requiring some public presentation of the team's project either through demonstrations, oral presentations, or written reports. This final step moves back to Quadrant #1 by making students experts who teach others about their project.

Oral presentations and final reports are by far the most common method of assessing capstone courses, adopted by 94% and 91% of programs respectively [7]. Assuming that the ability to publicly communicate a learned skill is the final step in social construction of knowledge, how well do public, oral presentations or final project reports measure students progression through the design process? In other words does measuring ability on the last step of the process provide a valid measure of students progression through the learning cycle? Can another form of communication provide insight into the private and individual steps of the capstone design learning cycle? To measure how well students progress through the engineering design process this work had students represent the engineering design process through an engineering block diagram. Block diagrams are common technique for representing the functional components of complex systems. In electrical engineering design projects the blocks represent physical circuits or functional software. Connections between the blocks represent wires or buses with specific voltages, frequencies, or data communication protocols.

Research Questions

This study asks the broad question of whether a student's ability to formally communicate aspects of the design process serves as a valid proxy measure of the ability to successfully contribute to a team-based design project. The research hypothesizes that a block diagram can serve as a written representation of the entire design process in a capstone course. The first research question is drawn from this assumption:

> **Are students who understand the design process at a higher point in the socio-constructivist cycle more competent in representing this understanding through a block diagram?**

Socio-constructivist theory states that both the time spent in social interactions with team members and a student's ability to internalize the design process are important in advancing through the learning cycle. Student success in design courses is often measured by communication of results through oral presentations or written reports. Furthermore students who are more active in participating with their team and seen as more valuable by team members should better understand the design process. The second research question is:

Does communicating the design process through a block diagram correlate with other commonly used measures of design ability?

There are several potential confounding factors pertinent to these research questions that are not addressed in this study. Under the assumption that the socio-constructivist model is a valid description of the engineering capstone design process, students begin to learn the engineering design process through social interactions with experts (faculty or teaching assistants) or more knowledgeable members of their team. We do not know *a priori* which students have gained understanding of the design process outside of the classroom, for example in internships [1]. Although communication and interactions between students are important factors in understanding design, this work does not measure the level or duration of such interactions directly even though the level of communication is correlated with success in design courses [13,14].

Methodology

The preparatory capstone course is taught using a cognitive apprentice approach. The first several weeks of the course focuses on design skills and the first social interactions of students are with experts who train them in electronic simulation, design, fabrication, and testing techniques (first quadrant of Figure 1). The block diagram approach to engineering design is taught in the classroom portion of the course along with teamwork and project management techniques. Following formal training, student teams are assigned a project and are required to submit a block diagram of the project in which the blocks (functional subsystems) are divided between team members. Each person on the team is individually responsible for one or more blocks. Teams subdividing tasks to individuals covers the second and third quadrants of the socio-constructivist learning cycle as students internalize what was learned and apply it to an individual problem. As individual students complete their tasks and the team integrates individual efforts (blocks) to complete the project, learning moves to the fourth quadrant.

To address the research questions three separate metrics of technical communication were developed to measure student ability to communicate the project-specific design process at different points on the socio-constructivist cycle.

Block Diagram Test

The first metric is a block diagram test in which students communicate the design of their project at different levels of technical detail. The test asked students to communicate the design process at the individual (component), team (subsystem), and class (system) level by drawing a block diagram with detailed connections between blocks. The block diagram test consisted of ten questions and was given in a one hour class period. The ten questions (minus course specific diagrams) are included at the end of this paper as an appendix. Questions on the block diagram test were classified in two ways. The first was which quadrant of the socio-constructivist learning cycle each question addressed. Of the ten questions, three questions covered the first and fourth quadrants with two questions in each of the second and third quadrants.

Questions were also ranked on two separate but related scales to measure the focus of a student's technical work as shown in Figure 2, below. One scale was formed by level of specificity or detail the question asked for. A high level of specificity (**S**) or detail required detailed technical knowledge of the system. At the other end of this scale general (**G**) questions asked for an overview of the system's function. One would expect a student who played the role of a project manager to have more general than specific knowledge, for example. There were four specific questions and six general questions. The second scale was determined by the level of localization within the system. On the local (**L**) extreme of this scale is a question about a single block of the system block diagram while on the other, distributed (**D**) extreme a representative question might be about a communication bus that connected all blocks. There were five localized and four distributed questions. These classifications of questions are designed to measure whether the level at which students understand a system impacts design ability. Students who have succeeded in internalizing knowledge and can communicate back to others are anticipated to have be more adept at distributed and general questions according to the socio-constructivist framework. The relation between the technical focus axes and four socio-constructivist quadrants will be discussed later in the paper.

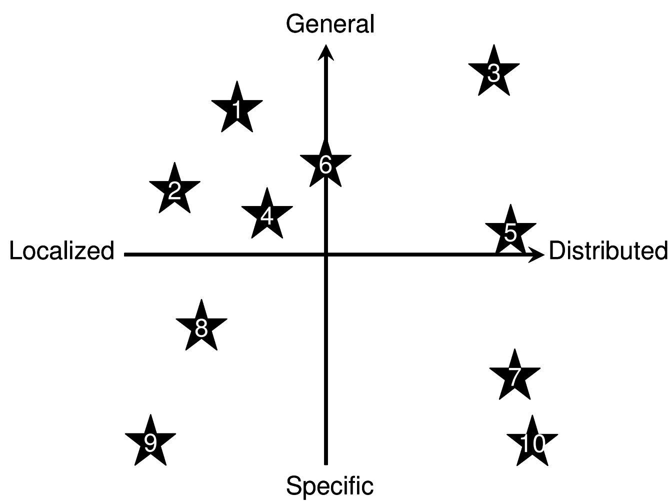

Figure 2: Distribution of the ten questions on the block diagram test on the S-G and L-D scales described in the paper.

The block diagram tests were graded using a rubric with a five point scale that was developed specifically for the block diagram test. To help eliminate bias, scoring was done by a panel of one faculty member, the four graduate student teaching assistants who support the capstone program, and two undergraduate REU students who had developed the tests and rubrics. Training sessions were organized to help calibrate grading and familiarize graders with the rubric before the test was administered. Grading was generally consistent between evaluators with fewer than 15% of the graded problems having a two point or larger difference.

Team Presentation

The second metric is a team presentation. The presentation is designed to be a short summary of the team's accomplishments and is made to a peer group of students. Student teams recorded a five minute presentation which was shown to the class. Each team then answered five minutes of questions. The presentations were required to cover three topics: an overview of the project and its goals, discussion of the design process, and details on technical specifications of the project. Referring to Figure 2 above, both specific technical detail and general overview information was required but students could choose to present a localized or distributed view of their project. Recording presentations was chosen for several reasons. One reason was to mitigate the confounding effects of performance anxiety. Although performance anxiety is an aspect of communication, it likely is not correlated with design ability which this study was investigating. Additionally recorded presentations were chosen to provide a more even playing field for the non-native English speakers in the class.

Presentations were graded by the panel mentioned previously using a rubric with a ten point scale; group calibration sessions helped ensure consistency in grading. The rubric rated the performance on the three required topics as well as the quality of communication and the quality of the presentation. The oral presentations were designed to test several steps in the socio-constructivist learning cycle. Note that an underlying assumption of this work is that public presentation of a team's results at a high level of expertise can only follow successful internalization of the design process. The way the presentation was assigned made it impossible to separate out individual contributions to the presentation from the work done as a team.

Individual Ratings of Oral Presentations

The third metric is individual student ratings of other team's presentations. This metric is designed to measure an individual student's discernment of the work of others. The evaluation of other's work is generally considered to be a high-level skill and should provide additional insight into a student's ability to communicate. Evaluating other teams "closes the loop" on the socio-constructivist learning cycle and may measure whether students can learn from other experts in a public and collective way.

Students were asked to rate other teams presentations using the same rubric used by the instructors. No calibration sessions were given to the students, however examples of good and bad oral reports were posted on the course website. To help ensure students gave fair ratings and did not "boost" each others grades, each student's score was modified by how their rating in each of the five grading categories compared to the average instructor/TA score. Points were added or subtracted from the student's score depending on the deviation from the average score of the trained evaluators on the five categories of the rubric. Scores that were within one standard deviation of instructor scores were awarded extra points, those within two standard deviations did not have points added or deducted, and students who were more than three standard deviations off had an increasing number of points deducted the further their scores deviated.

Comparisons with "Design Characteristics"

The numerical scores of the block diagram test and individual ratings of oral presentations were correlated to measures of student characteristics often assumed to be indicative of "design ability". If the socio-constructivist framework describes the design process, we expect a positive correlation between measures of student characteristics related to design and performance on the measures of communication. Students who have spent more time internalizing the design process should be better able to communicate the format and structure of their project.

Since team-based engineering design draws on many domains of knowledge, trying to directly measure student characteristics that facilitate success in engineering design is difficult. Furthermore there is, as yet, no universally accepted group of characteristics or skills that are recognized as fundamental to engineering design. Most capstone courses use ABET outcomes to determine at least part of the course outcomes [1]. Lacking an accepted set of skills and knowledge that contribute to design, design characteristics were drawn from other design courses and ABET outcomes. Both graded and ungraded student assignments were used as proxy measures for design characteristics. Most of these proxy measures are in the process of being validated, although some are drawn from widely accepted metrics. The set of skills that were measured and that are assumed to contribute to understanding of the design process and an ability to contribute to this process are:

- *An ability to function on a team.* To measure team performance students completed anonymous peer evaluations that used behavioral anchors [20]. The peer evaluation gave each team member a rating based on their perceived attitude and value to the team, a rating of their contribution to the efforts of the team, and an overall rating that was used to scale grades. Using peer evaluations to scale grades can skew results.
- *An ability to communicate technical results through written reports.* Reports were written by teams three times during the semester and the end of each project. Each report was graded using a rubric by a panel consisting of three graduate students or faculty members who had been trained in rubric-based grading. It is not possible to measure scores of individual students, but since teams were reorganized for each design project the aggregate report score is used. This is not expected to be a strong measure of individual student ability.
- *An ability for time management.* Independent of the design projects the design course had multiple short assignments due each week which were tracked for each student. We use the number of assignments missed over the semester as a proxy measure of individual student's time management skills. We are currently investigating better metrics.
- *An understanding of the concepts underlying electrical engineering.* At the end of the semester a concept inventory was given to all students drawn from one being created nationally [21]. The questions on the concept inventory were chosen by at least two faculty from each sub-area of electrical engineering to represent conceptual knowledge that (a) all students should know without review, and (b) represent fundamental concepts that are taught to all students in the program.
- *The student's grade point average* was included as an indicator of overall academic ability. GPA has been used as a means to easily distinguish between students in forming teams [22].
- *Students self reported effort in the course.* At the end of the course a short survey asked students to estimate the average number of hours per week spent on the capstone course over the semester.
- *Students' perception of authenticity.* At the end of the course students were asked to complete a short survey on how authentic an exposure to the engineering design the capstone course was. Results of this survey were used, but the survey was somewhat informal and is not a validated measure of relevance or authenticity.

The quantitative scores on the seven characteristics that contribute to design were correlated with the student scores on the block diagram test and individual student ratings of other teams oral presentations. Based on the socio-constructivist framework applied to the engineering design process we expect that students who have more design skills as measured by the seven characteristic measures above will advance through the design process learning cycle of Figure 1 more rapidly and demonstrate a higher ability on questions in quadrants three and four as well as questions that are general and distributed.

Skills, characteristics or topics common to many design courses that may impact "design ability" that were not measured in the first round of data collection include: project organizational skills, leadership skills, and prior experience in design. Prior experience is being currently being assessed currently through a survey given to students and will be reported at the conference. One caveat on the approach used is that although a student may be capable in multiple individual domains does not necessarily mean those domains can be integrated to confer design ability. Currently we have no way to measure integration of these abilities.

One other metric often used to measure "design ability" that was not used in this study is faculty evaluation of how well the design projects function [7]. Project functionality was not measured since we were unable to develop a detailed rubric and it was felt that without a rubric grades would be too subjective. In addition the large differences between individual projects, and the large number of possible confounding effects that can affect project completion made functionality a questionable measure of design ability.

Findings

The class size of the first capstone course at the start of the semester was twenty students. Two students dropped in the first two weeks and one other student did not complete the course leaving a sample size of $N = 17$ students. The relatively small class size makes it more difficult to draw statistically significant correlations from data.

Design Characteristics

We performed correlations between the seven measures of characteristics to determine if scores on one measure could be used to predict scores of other characteristics. Values of $p < 0.1$, $p < .05$, and $p < .005$ are reported. The $p < 0.1$ values are of questionable validity but will be further measured in future iterations of the course to see if they improve with larger sample sizes. Three characteristics showed statistically significant correlations as shown in Table 1 below. Three measures from the peer evaluation are shown that represent attitude and value, effort perceived by peers, and overall value to the team. These three measures are highly correlated. Surprisingly strong statistically significant positive correlations also exist between peer scores and scores on the concept inventory, with weaker correlations of questionable significance between peer ratings and grade point average. No other characteristic measure was correlated at a significant level except for a strong negative correlation between self-perceived time spent on the course and peer evaluations of attitude. This is not further investigated here. It may be that the other measures of characteristics that support design are valid but uncorrelated or that the metrics used have little significance.

	Peer: Attitude	Peer: Effort	Peer: Overall
Peer: Attitude			
Peer: Effort	0.78 (p<.005)		
Peer: Overall	0.86 (p<.005)	0.86 (p<.005)	
Concept Inv.	0.71 (p<.05)	0.72 (p<.005)	0.68 (p<.005)
GPA	0.44 (p< .1)	0.42 (p<.1)	0.42 (p<.1)

Table 1: Statistically significant correlations (r) between the seven student characteristics described in the previous section that are hypothesized to support design.

Block Diagram Test

On the block diagram test questions on different categories of the socio-constructivist cycle were strongly correlated as seen in Table 2. The correlation of the mean student score in different categories is shown in Table 2(a). The correlation was weakest between quadrant one questions and questions from other categories while questions from categories two and four were most strongly correlated. Table 2(b) shows the percentage of *individual* questions from each quadrant that had a statistically significant positive correlation with questions from other categories. The questions that cover quadrants two and four are seen to be better correlated with the other questions on the block diagram test.

	Mean Q1	Mean Q2	Mean Q3
Mean Q1			
Mean Q2	0.58 (p<.05)		
Mean Q3	0.49 (p<.05)	0.73 (p<.005)	
Mean Q4	0.58 (p<.05)	0.72 (p<.005)	0.69 (p<.005)

Table 2(a): Correlations between the mean scores on different categories on the block diagram test.

	Q1	Q2	Q3	Q4
Q1	0%			
Q2	17%	100%		
Q3	0%	50%	0%	
Q4	11%	67%	50%	33%

Table 2(b): The percentage of individual questions that have statistically significant positive correlations with questions in other categories.

Scores on questions in the first quadrant–collective knowledge communicated in class—do not predict student answers on other questions as well as scores for questions from the second through fourth quadrants. On the ten question test three questions were from quadrants one and four, and two each from quadrants two and three. The mean score on questions assigned to each quadrant were similar with the exception of quadrant four which had a lower mean score (0.3 points on a four point scale). The lower mean score for quadrant four was statistically significant compared to the mean of quadrant two and three questions. The standard deviation of scores was higher on questions from quadrants two and four.

Correlations of student scores were also done for the specific vs. general knowledge axis and localized vs. distributed knowledge axis. The correlation between specific and general questions was $r = 0.73$ ($p<.005$) and that between general and localized questions was $r = 0.70$ ($p < .005$).

Students who performed well on one set of questions also tended to perform well on the other. The percentage of individual questions that have statistically significant positive correlations are shown in Table 3(a) and Table 3(b). From the percentage of individual question responses that have statistically significant correlations, with we conclude that questions on the block diagram test are better predictors of *same* category performance—i.e. S-S, G-G, D-D, or L-L—than are cross category questions. The mean of specific and general questions are similar with the standard deviation of scores on specific questions being higher than general questions. Questions about localized aspects of the block diagram have a higher mean than those about distributed aspects (4.1 compared to 3.8) and also have a slightly higher standard deviation but the difference between the means was not statistically significant.

	S	**G**
S	50%	23%
G	23%	33%

Table 3(a): The percentage of individual specific (S) and general (G) questions that have statistically significant positive correlations with other questions.

	D	**L**
D	40%	35%
L	35%	50%

Table 3(b): The percentage of individual distributed (D) and localized (L) questions that have statistically significant positive correlations with other questions.

Student scores on quadrant 4 questions had a lower mean than those of any other question grouping. The difference in means was statistically significant between quadrant four and specific, localized, and quadrant two questions. Quadrant two questions had the highest mean and were significantly higher than those of distributed, general, and quadrant four questions. These differences lend some support to interpretation of the block diagram test using the socio-constructivist framework since students who are focused on specific tasks and do well on those questions may not have reached the point or be able to see the design task from the point where they integrate their individual work into the team's design project. Similarly students who take on responsibilities that focus on aspects of design distributed among different blocks (i.e. coding, designing bus or communication protocols) or who have tasks that are general in nature may have difficulty on questions that focus on specifics of individual blocks.

Oral Presentation Peer Ratings

Similar methods as described above were used to analyze peer ratings of team presentations. Separate numerical ratings (1 – 10 scale) were given for:

- the team's design goals (general and quadrant one),
- presentation of detailed specifications (specific and quadrants two and three),
- the explanation of the overall design process (quadrant four).

Two other peer ratings were not related to the socio-constructivist model, the ability to communicate and the visual quality of the presentation. These were intended to statistically remove the confounding effects of presentation quality on ratings, but this analysis has not yet been performed. Comparing peer ratings on different sections of the report, the mean peer ratings were highest on the presentation of goals and lowest on the design process at a statistically significant level ($p < .05$). This supports the socio-constructivist model of development from quadrant one to quadrant four. Expert ratings also followed this trend, but not at a statistically significant level. Student ratings of the design process and specification sections were positively correlated with each other ($r = .50$ to $r = 0.75$) at a statistically significant level. Neither of the process or specification sections had a statistically significant correlation with goals.

Students rated peer reports higher than the instructors by an average of 1.9 points on a 10 point scale. The standard deviation of all student rating scores was 1.36 while that for instructors was 1.87 which we interpret to mean increased discernment among the instructors compared to the students. There was no statistically significant difference between student and instructor ratings on different sections of the oral presentations. Since the 1.9 point difference between mean student and instructor scores is close to the standard deviation of instructor scores, most students earned some extra points on the exam (average of 6.4 with a standard deviation of 4.6). Only two students out of seventeen lost points by giving high peer evaluations which we interpret to mean the technique used to minimize grade boosting was successful. The difference between student and instructor ratings of the five categories of the presentations were highly correlated ($\rho = .50$ to $.75$) at a statistically significant ($p<.05$) level with the exception of the section covering goals (Quadrant 1).

The ratings given by individual students and the difference between student and instructor ratings on different sections of team presentations generally predict ratings on other sections with the exception of team goals which correspond to the lowest level of the socio-constructivist learning cycle. The validity of predictions based on the difference between student and instructor scores is much higher than the that using student scores themselves.

Design Characteristics Correlated to Communication Measures

Finally correlations were done between the proxy measurements for design characteristics and scores on the block diagram test and differences between student and instructor scores on oral presentation ratings. Here we attempt to determine if the block diagram test and student ratings of reports were reliable predictors of aspects of "design ability". For the block diagram test there were no statistically significant correlations between the self reported relevance of the project or hours per week devoted to the course. Nor were there any significant correlations between the block diagram test and proxy measures for time management. Since these measures did not correlate with other measures of student characteristics that support design it is likely the survey questions need to be improved and the number of missed deadlines is simply not a good measure of time management. Different proxy measures will be used in future iterations of the course.

Student scores on the concept inventory were only statistically correlated with questions from quadrant four ($r=0.54$, $p < .05$) and specific (S) questions ($r=0.50$, $p < .05$). Grade point average was only significantly correlated with questions from quadrant two ($r=0.51$, $p < .05$). All categories of questions on the block diagram (all four quadrants of the socio-constructivist cycle, specific-general, and localized-distributed) were strongly correlated with the overall peer evaluation score. The highest correlations with $p < .005$ were for questions in quadrant 4 with $r=0.84$, compared to $r=0.51$, 0.62, and 0.54 for quadrants 1 to 3 respectively which were also less significant ($p<.05$). Similarly specific questions had a higher correlation with peer evaluation scores than did general questions (r=0.80 vs. r=0.64) and localized questions were more closely correlated with peer evaluation scores than were distributed questions (r=0.76 vs. r=0.65).

Since the overall peer evaluation consisted of both an attitude and value rating as well as an effort rating we examined which of these was more closely correlated with scores on the block diagram test. The significance of the correlations of perceived effort were stronger than those of the perceived value. The peer evaluation effort ratings had correlations that range from r=0.65 to r=0.86 with p<.005 for all question categories except quadrant 1 where r=0.63 with p<.05. The mean correlation of value ratings over all categories was r=0.71 with p<.005. Value or attitude ratings were not as significantly correlated with questions from quadrant one and had an average correlation of r=0.55 with p<.05. The differences of the mean correlation between different categories of questions on the block diagram test and peer ratings of value and effort is itself statistically significant.

Comparing the difference between student ratings of other team's presentations and the scores given by experts, there are no statistically significant correlations between any of the characteristics that contribute to design and either raw or difference scores in any of the five topics the oral presentations were rated on. If one sets the level of significance at p < 0.1 there is a positive correlation of r=0.41 between scores on the concept inventory and the difference between student and expert ratings on the section of the presentation that covered the design process. These measurements will be repeated in the future with larger sample sizes which may establish if this correlation is real or not.

Summary Analysis and Impact on Practice

The research reported in this paper discusses the development of two new methods of measuring student's "design ability" that focused on different stages of the design process. Since no widely accepted measures of design ability exist, the project measured student characteristics that were expected to be correlated with the ability to perform engineering design and ways that are currently used to assess capstone design courses [1].

The first measure of "design ability" was a written block diagram test given in class. This test asked students to recreate the block diagram of their design project. Questions on the test were designed to measure student understanding at different points on the design process as mapped to the four quadrants of Harré's interpretation of the socio-constructivist learning cycle [19]. The questions on the block diagram test were also categorized on two axes representing the focus of technical work. The first axis rated whether questions asked about specifics of the project (i.e. technical detail) or information general to the design project. The second axis was whether the questions asked about a localized part of the design (i.e. individual blocks) or features distributed throughout the design (i.e. connections between blocks). There is not intended to be a one-to-one correspondence between the four quadrants of the socio-constructivist learning cycle and the technical focus axes. However, since learning the design process parallels student work on the engineering design project a rough correspondence between the four quadrants and the general-specific and localized-distributed axes can be made as shown in Figure 4. It is best to imagine that the angle between the two sets of axes can vary by a large amount depending on the specific phrasing of questions.

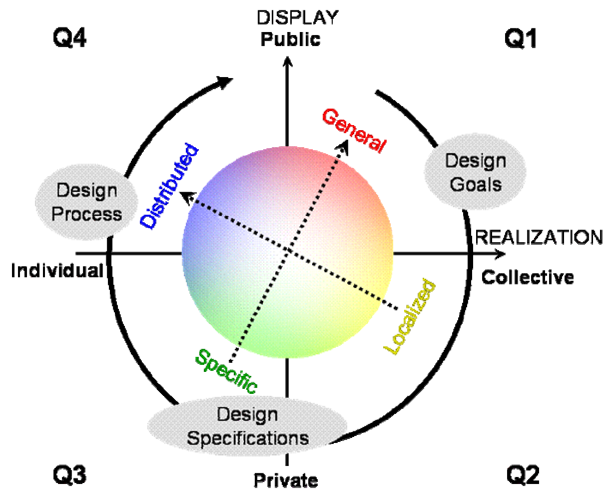

Figure 4: Rough correspondence between technical focus axes (dashed) and socio-constructivist axes. The three sections of the oral presentation are shown as grey ovals.

To determine if communicating the design process through a block diagram gives insight into a student's progress through the design process scores for questions related to different quadrants were compared. Analysis of the correlations between sets of questions showed that:

- Scores between questions on different quadrants and different technical axes were highly correlated. Students who performed well on one section performed well on the examination overall.
- The correlations to first quadrant questions—representing design knowledge given to students in class—were generally weaker. The ability to represent the project at the lowest step of the process did not predict performance on higher stages of the design process.
- In support of the socio-constructivist model students scored less well on questions from quadrant four than from the other quadrants. While we ideally would anticipate decreasing scores with increasing quadrant, this was not observed in the first iteration of the block diagram test given to students.

Having students represent their project through a block diagram where questions are drawn from different stages of design provides some insight into their knowledge of the design process. In this first iteration of the block diagram test there is not yet the level of specificity that is desired to separate the second and third quadrants.

Two additional axes were used to analyze the technical focus of different questions on the block diagram test. It was found that:

- Scores on different axes were highly correlated.
- Correlations were higher between questions from *same* category.
- There was no statistically significant difference between overall mean scores on the different classifications of questions

From these results we hypothesize that students choose or are assigned a role on a team that focuses on either specialized or general application of design principles. Students may work primarily within this role and not be able to communicate other aspects of the design process as well as those within their role. The fact that students do better on similar questions may also reflect different methods of thinking about problems taught in the different areas of specialization within our program, but this was not tested.

Considering relations between questions focusing on the learning cycle and questions analyzing the technical focus of the block diagram test:

- Correlations were high.
- Correlations between different questions that lie close to each other in Figure 4 (e.g. general and quadrant 1) were higher than correlations between questions that are distant (e.g. distributed and quadrant 2).
- Students performed statistically better on specific and localized questions than they did on questions from quadrant 4.

These results lend some support to the hypothesis that student learning in capstone design courses occurs through a socio-constructivist cycle. Technical focus questions that measure student knowledge of different aspects of the block diagram are related to the quadrant in which these skills are used. The fact that students performed better on quadrant two questions than on distributed questions also supports this view.

To determine if students who better understand the design process are more competent in representing this understanding through a block diagram, the seven measured design characteristics were correlated with block diagram test scores. The block diagram test had significant positive correlations with teamwork, and less strong correlations with student understanding of concepts, and overall academic performance. On aspects of peer evaluation, the correlations were strongest with the perceived effort put forth by others on the team. The other measures of design characteristics were not correlated at a statistically significant level. It may be that the other characteristics are simply uncorrelated or that measures of the characteristics were flawed. Other measures will be used in the future to clarify the relationships.

From the internal correlations of block diagram test questions and external correlations to design characteristics it is likely that students who perform well on the block diagram test are those who are most engaged and knowledgeable about the team design project. One interesting question for future research is how the block diagram test affects students.

Comparing student ratings on peer presentations to instructor ratings to measure discernment had several internal consistencies that fit the socio-constructivist learning cycle. The three general categories of the oral presentation where student and instructor ratings were compared are shown as the grey ovals in Figure 4. The difference between student and instructor scores using the same rubric were better predictors than scores alone. Both student and instructor scores were highest on project goals that had been communicated to teams in quadrant one, but the difference in scores on goals did not predict student performance on sections of the presentation that focused on higher quadrants. Team's explanations of the design process—requiring knowledge from several quadrants—were the lowest rated, but were good predictors of how closely student and instructors rated other quadrants. These measures of student discernment were not correlated to any of the seven measures of student characteristics that support design, however. It may be that discernment, at least on peer presentations, has little correlation with engineering design. It may also be that students rating of other teams was strongly affected by interactions within their own team which skewed results. Significant further work is needed to clarify the role of discernment in the socio-constructivist learning cycle and in the engineering design process.

As far as the impact on other senior design courses, we have chosen characteristics that are associated by many programs as representing critical elements of capstone courses. A valid proxy measure of an individual student's ability to perform team design projects can help instructors better assess individual student performance in capstone courses. The internal consistencies of the block diagram test along with the correlations to other characteristics associated with design indicate that with further development this can be a useful tool in capstone courses. This is particularly true since it can be given in one class period. Scores on the block diagram test can help to support or refute peer evaluation scores, particularly when used to assign grades. These measures could also provide quantitative measures of student abilities in technical communication that can be used in the ABET CQI process.

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Appendix A: Block Diagram Test Questions

Question 1: Identify the subsystem(s) your team worked on by putting a star in the boxes on the block diagram on the previous page.

Question 2: Briefly summarize the function of the subsystem(s) *worked on by your team you identified in Question 1.* The summary should describe the purpose of your team's subsystem and its role in the overall gaming system (**use about 50 words**).

Question 3: Draw inputs or outputs on the system block diagram **to illustrate** how your subsystem(s) communicates with the other parts of the system. Indicate using arrows the direction of communication.

Question 4: For each of the inputs and outputs of your subsystem you drew for question #3, write a **brief explanation of about one sentence** on what the connections are or what they do.

Question 5: Briefly summarize in no more than 50 words the function of all the other subsystems your team's subsystem(s) communicates with or connects to.

Question 6: Draw a block diagram of your team's subsystem on the blank sheet after this page.

Question 7: Draw connections between blocks and Provide any ***brief*** notes needed to understand the diagram.

Question 8: In **no more than 100 words per block briefly describe** the function of ***each*** block of your team's subsystem.

Question 9: **Describe your own contribution to the project** by an **in-depth** technical description in approximately 150 words of the function of the **block(s)** you had primary responsibility for. Make sure you give detailed information on signal levels, the components used, variables or subroutines in code, or other appropriate technical information.

Question 10: Give an **in-depth** technical description in approximately 100 words of the **connections or communications** between the blocks you had primary responsibility for and the rest of your team's subsystem or the system as a whole.

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