A Functional Decomposition Test for Formative/Summative Evaluation of Capstone Design

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This paper reports on the development and implementation of a formative/summative examination used to measure students knowledge and understanding of functional decomposition. The examination is given in a capstone course in the electrical and computer engineering department of a public, research intensive university. The closed-book examination, termed a "block diagram test", is given to individual students midway through the capstone course. The examination asks students to describe their design project through an engineering block diagram. The examination assumes the socio-constructivist theoretical framework of the Vygotsky Cycle to explain how students learn design, and thus to map questions to different quadrants of Harre's display and realization axes. The exam is both formative and summative since it is given early enough in a semester to provide feedback to students on their understanding while simultaneously measuring an individual's understanding of a team design. The block diagram test has undergone significant testing and revision over a four year period. Results of the test development are reported along with comparisons of test scores to other measures of learning and teamwork.

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Background

Design—from the freshman year to capstone courses—is increasing in importance in undergraduate engineering programs. While engineering analysis courses focus on domain-specific knowledge, design courses emphasize application of a broad spectrum of knowledge in narrow contexts[1]. Design courses are seen as important elements of an engineering curriculum due to their impact on students and significant role in ABET assessment and accreditation[2].

One of the key elements or skills of engineering design is functional decomposition, the process of dividing a complex problem into manageable pieces[3]. A block diagram is the visual representation of functional decomposition, a system representation based on function that also specifies the connections between parts of the system. In the capstone course reported here, functional decomposition is the first step in project definition and additionally serves as a mechanism to support both individual accountability and effective teamwork. This paper reports the development of a formative/summative examination over functional decomposition given in the first of two capstone courses in the electrical and computer engineering program at a large, research intensive public university. The examination is given to individual students to test their understanding of their team's functional decomposition (summative) as well as provide feedback to individuals and teams on possible issues with their functional decomposition (formative).

As described in the next section, the examination is built on a socio-constructive framework, and different questions on the examination measure different stages of the learning cycle. Student scores on the exam have been collected for approximately three years, and are compared to other measures of performance in the capstone design course.

Theoretical Framework

The functional decomposition examination, i.e. "block diagram test", is based on the Vygotsky cycle, a socio-constructivist model of learning. This model assumes that students' build an understanding of design through material presented to them by experts, discussions of their project with peers, and their own struggles to place what is learned in personal frameworks. The Vygotsky cycle was initially proposed by Rom Harré[4] and further refined by Gavelek and Raphael[5]. The Vygotsky Cycle, shown in figure 1, has received recent interest as a model of learning in literacy, art, education, and languages[6]; fields which require divergent thinking and making value judgments based on imperfect information[7], similar to engineering design.

In the Vygotsky cycle, an individuals' understanding develops in four sequential transitions between the quadrants of figure 1. Each of these transitions represents action on the part of the individual:

• Appropriation: In quadrant one an individual is given information in a public, social setting (i.e. classroom) then selects or appropriates aspects for themselves.

Appropriation moves the student from the public display and group or social realization/conception of knowledge, “This is what the class taught", to ownership of this social knowledge, “This is what I learned".

• Transformation: As the student uses (internalizes) what they learned about design, both the design and the students are transformed by moving from individual ownership (display) of a social depiction of knowledge in quadrant two (“This is what I learned”) to developing their own personal realization of what this knowledge means, quadrant three (“This is what I think”). Transformation is a critical aspect of design due to the vagaries of application and need for tacit knowledge[8].

• Publication: Since the individual’s understanding developed in moving from quadrants two to three are not necessarily correct (i.e. a misconception) or do not match the accepted understanding of the cultural group, in this case the design team, individuals must publish their conceptions to others to prove validity. By public display of knowledge the student moves from quadrant three (“I think this true”) to quadrant four (“I affirm this is true”).

• Conventionalization: When the individual’s learning is fully integrated back into the public social domain—i.e. accepted by their team—they move from quadrant 4 back to quadrant 1. Now the student becomes an expert on their part of the system, sharing knowledge with others.

In the context of engineering design, the Vygotsky cycle describes how a student's understanding develops to match the sub-culture of expert designers. In developing the block diagram test, it was assumed that as an individual’s knowledge is constructed internally and externally and the level of understanding can be measured using questions focused at each quadrant of the cycle. Ideally such an examination can provide feedback on students’ progress in a design course.

Implementation

In the capstone class teams were taught the design cycle and the functional decomposition process through textbook[3] readings, formative on-line quizzes, on-line video lectures, and active learning in during weekly class meeting. Each team was given an electronic design project; the first step in the design project was for teams to develop a block diagram of their project. Teams then assigned parts (blocks) of the project to individual students who were responsible for each step of their block's design process. All blocks had to be independently testable functional units. Teams then defended their functional decomposition in class before the instructor and graduate teaching assistants. Each team received feedback on ways to improve the functional decomposition of their project.

The block diagram test is given two to three weeks after the team's presentation of their project's functional decomposition, about the time students have performed a first iteration of the process of constructing functional prototypes of the blocks they are individually responsible for. Before the test is given students researched how to implement their blocks.

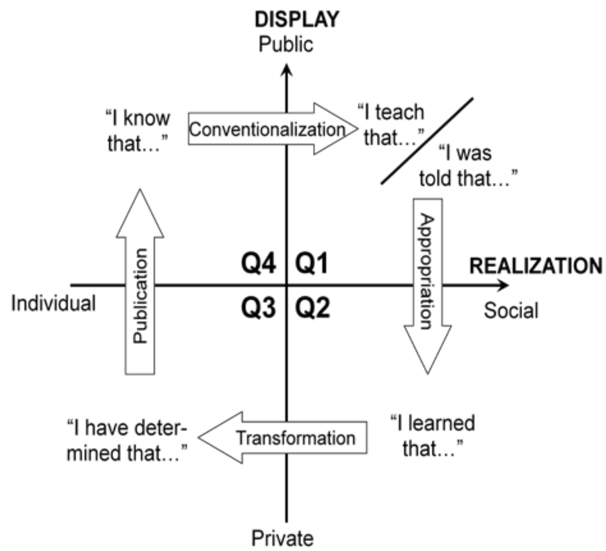

Figure 1: The Vygotsky Cycle as interpreted by Rom Harre and used to design the block diagram test.

The closed-book, closed-note test, which has undergone several minor revisions, is given in class with a one hour time limit. The test asks students to communicate the design process at the individual (block), team (subsystem), and class level by drawing or annotating level 1 (system), and level 2 (subsystem) block diagrams with technical details on function and the connections between blocks. Note that while a team’s answers will (ideally) be the same for system descriptions, since each student is responsible for a different block, individual answers will vary for the level 2 diagram.

Questions on the block diagram test were classified in three ways. The first classification was by which quadrant of the socio-constructivist learning cycle each question addressed. The second classification was whether the question asked for information about the system as a whole, or for one of the subsystems or blocks. The third question classification was whether the question asked for descriptive or technical information. Descriptive questions provide overview or user information while technical questions typically sought quantitative details of operation.

The block diagram tests were scored using a rubric with a five point scale; the rubric was adapted as the test evolved. To help eliminate bias, scoring of each test was done by a panel of one faculty member and at least two of the four graduate student teaching assistants. When there were large discrepancies between scores, the scores were discussed and a consensus was reached. Grading was generally consistent between evaluators, but inter-rater reliability was not calculated.

The question classifications were designed to determine what type of questions were most discerning in measuring individuals' understanding of their design and the process of functional decomposition. The hypothesis to be tested is that scores will decrease for quadrants later in the Vygotsky Cycle, and that students who are more "adept" at design will have higher scores, particularly for questions aimed at quadrants further along in the design cycle. Since it is not possible to directly measure "design ability", several proxy measures were proposed, including peer evaluation scores (peers' perception of design ability), student grade point average (hypothesized to be correlated to test taking ability), the students score in the design class (excepting the block diagram test score), and score on a conceptual examination (understanding of concepts) given to students as part of department ABET accreditation.

Results

Six semesters of data were combined for this analysis, with a total sample size of N = 103. Although there were some minor differences between exams due to ongoing revisions, these were ignored in the analysis. Three analyses were performed. The first compared the mean score of students on questions written to address quadrants one through four of figure 1. The second analysis looked at the mean of scores of the questions defined as either "system" vs. "block" or "descriptive" vs. "technical". The final analysis sought to determine whether the other factors that might determine student performance in the capstone design class such as scores, peer evaluations, or grade point average were predictors of overall scores on the block diagram test.

Analysis of variance (ANOVA) showed that students scored highest on quadrant two, Q2 ($\mu = 3.80$, $\sigma = 0.60$), followed by Q3 ($\mu = 3.44$, $\sigma = 1.13$), Q1 ($\mu = 3.40$, $\sigma = 1.06$), and Q4 ($\mu = 3.26$, $\sigma = 0.97$). The scores on Q2 are significantly higher than all other categories ($p < .05$). The fact the exam was given midway in the design project may account for the significantly better performance on quadrant two questions. The Vygotsky cycle model of how students learn design, would predict that midway through a project scores would be highest in Q2. While the low scores on quadrant #1 are surprising, relatively few questions addressed this quadrant. Note that according to the Vygotsky cycle, quadrant 1 is both the start and end point of student learning. A review of the questions on the exam indicated they asked for knowledge that students could only be expected to have after the step of conventionalization (figure 1).

To determine the differences in students' ability to describe their portion of the system (block) or the team's overall design (system), a paired samples t-test was used. Questions on individual students' work (blocks or subsystems) scored significantly higher ($p < 0.05$) than questions covering the system as a whole, indicating at the point in the project the test was given, students are more familiar with the portion of system they are responsible for designing than the system as a whole. The difference between the means, while significant, was not particularly large, 0.25 points on a 5 point scale. The t-test was also used to determine whether students performed better on questions that had students provide technical details or a more descriptive explanation of project functions. The score on descriptive questions was significantly greater ($p < .005$) than the scores on technical questions. While the difference in the means was 0.2 points, the variance of scores on the descriptive questions was small, indicating most students performed well on these questions.

Does the block diagram test measure students' ability to learn, perform, and/or report functional decomposition, or is it strongly affected by other academic skills? Are students who perform well on the test valued by peers? A linear multiple regression was used to determine if 1) the factors mentioned earlier were correlated with performance on the block diagram test and, 2) block diagram test scores were correlated with how peers viewed design performance. In general there were few correlations between scores on the block diagram test and proxy measures of academic ability; i.e. the students' GPA or score on the concept inventory. Conceptual understanding was correlated with questions from quadrant two ($p < .005$), but with $R^2 = 0.23$ had little explanatory power. Students' performance in the class, determined by the overall course grade, were not correlated with scores on the block diagram test overall, or the scores for any of the four quadrants. Descriptive questions, however, had a slight negative correlation ($p < 0.05$, $\beta = -0.19$) to class performance. The overall score on the block diagram test and the overall score on the peer evaluation score, hypothesized to be a proxy of peer's perception of design ability, were significantly correlated ($r = 0.35$, $p < .001$). Further investigation showed that the correlation came almost entirely from Q4 questions. When only Q4 questions were considered, the correlation improved ($r = 0.42$, $p < .001$). While there was little difference in the ability of descriptive or technical questions to predict peer evaluation scores, system questions scores were correlated ($r = 0.42$, $p < .001$) with peer evaluation scores while performance on individual block questions were uncorrelated.

Application

The block diagram test was given midway through a capstone design project both to inform students of how their design knowledge was perceived by experts and to determine students' ability at functional decomposition. The results from the exam support the socio-constructivist view of learning described by the Vygotsky cycle. The exam was summative in the sense that it helps the instructor determine individual student accomplishments at a fixed point in the design cycle. However, the reason the test was given midway through the semester was to ensure that all students on a team studied (and in some respects memorized) both their team's system block diagram and a functional decomposition of their own part of the project. In this respect the block diagram test is formative, since it lets students get feedback on their own understanding of their knowledge of the design. Thus while it is hypothesized that the block diagram test may improve performance on the capstone project, since no control group (i.e. not given the block diagram test) is available, the hypothesis has not been tested. An additional possibility is to give the exam in a pre-post format as an ABET assessment tool. Giving the exam early and late in the course would allow faculty to see both improvements in functional decomposition and changes to design project.

Beyond the benefits of having students study their team's block diagrams, giving a functional decomposition test in a capstone class provides faculty valuable feedback on student understanding of their individual design assignments and how well the team understands system design. While the block diagram test is given midway through the project in the course discussed here, the exam could also be given at the end of the course as a purely summative measure to help faculty determine individual contributions in a team design project. The test has led to considerable insights about areas in which students do not have sufficient preparation including understanding and describing system interconnects and writing technical specifications.

A significant number of improvements can be made to the functional decomposition test. One of the most difficult issues is grading questions on individual subsystems since each "correct" answer is different. While for this work a rubric has been used for grading; current work is focusing on more focused questions graded by checklists, and qualitative evaluations of short explanations and annotations. Another issue is the time required for the test when students have to recreate a system block diagram from memory. Future iterations of the exam will be produced with a block diagram submitted by the team, and ask students to annotate and explain features of their design. A more significant modification under consideration is adding questions about actions students take to move through the design process; i.e. how they advance through the Vygotsky cycle.

Conclusions

A "block diagram test" was developed to measure students' knowledge of functional composition for their teams' designs. Based on a four quadrant socio-constructivist model of how students learn design, it was observed that questions in higher quadrants were more discerning measures of student understanding, providing guidance for development of other capstone design tests. Similarly questions that were focused on technical descriptions and system design and interconnection were more discerning than descriptive questions or questions that asked students to explain their own technical work.

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