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Transformative Experiences: Scaffolding Design Learning Through the Vygotsky Cycle*

ALAN CHEVILLE
Oklahoma State University, Stillwater, OK 74078, USA. E-mail: kridnix@okstate.edu

The motivation for this work was to create an engineering design course to develop students' abilities in electronic design. A 'transformative' design course was created by merging the design process found in most engineering design textbooks with the Vygotsky cycle. The Vygotsky cycle, drawn from socio-constructivist theories of learning, describes how both learners and their interpretation of knowledge are transformed by the learning process. Research identified elements of how students learn design, direct and indirect learning goals, and project constraints. A course model classified design learning through a taxonomy, identified aspects of design students lacked experience in, and scaffolded learning using the Vygotsky cycle. Following implementation of the design course, both quantitative and qualitative evaluation was used to measure student learning. Evaluation shows that although most of the direct and indirect course goals were met, there are aspects of design that students fail to master.

Keywords: Vygotsky cycle; capstone; design process; engineering design

1. INTRODUCTION

DESIGN AS AN activity is increasing in importance in undergraduate engineering programs. From freshman courses to capstone courses, design is seen by proponents as a vital element of learning engineering [1]. While analysis courses focus on narrow, domain-specific knowledge, design courses emphasize application of a broad spectrum of knowledge in narrow contexts. The importance of design courses arises from their impact on students and disproportionate role in assessment and accreditation [2]. In many cases student design projects actualize the National Academy of Engineering's vision for the next generation of engineers outlined in *The Engineer of 2020: Visions of Engineering in the New Century*.

Despite the importance of design experiences to students, faculty who teach design face both pedagogical and personal risks. Pedagogical risks arise from the difficulty of articulating what design actually entails, balancing classroom instruction with project-based learning, the breadth of pedagogical and technical knowledge needed, and objectively evaluating course and learning outcomes [3, 4]. Personal risks—those which can potentially jeopardize one's career—include balancing effort with rewards, potentially poor student evaluations, and the disproportionate importance of design courses to department accreditation. The struggle to balance such issues has resulted in many models of capstone design courses [3].

In answer to recent calls for 'useful sharing' [5], this article describes the process through which research on how students learn design informed the iterative design of a new course. The article is organized around the steps of the five step design process followed in the class: *research → model → implement → measure → communicate*. While the linear flow of ideas found in a journal article gives the impression that course design proceeded in a smooth, linear fashion in actuality the course was developed iteratively over time and the article reflects activities that supported design learning rather than the blind alleys.

2. RESEARCH ON DESIGN

Most design processes begin with problem identification and needs specification [6]. In this case the need was to modify an existing capstone design course with a high failure rate that acted as a bottleneck in the engineering degree program. The Electrical and Computer Engineering (ECE) program at Oklahoma State University (OSU) offers a sequential two course capstone design sequence taken in the senior year. The first course is taken by first-semester seniors to prepare them for independent, team-based design projects. In 2004 the first capstone course consisted of a series of tightly constrained electronic design projects performed by individual students. Grades were determined by quantitative performance metrics (i.e. signal to noise ratio, accuracy of gain, etc.). Responses to a survey of students who had completed the course showed students felt fundamentally unprepared for the design experi-

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ence. A representative comment was '. . . *all of the undergraduate level courses did not build up to this course. This was like 'wanting to fly without even knowing how to crawl*'.

Prior work on engineering design was researched before modifying the design course to situate the course on a sound theoretical foundation. Surprisingly, there is a wide range of conceptions even for something as fundamental a definition of engineering design. The definition used was drawn from the Accreditation Board for Engineering and Technology (ABET) [7]: '*Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic science and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation.*' This definition is often represented as the design process, shown in Fig. 1, taken from the text used in the design course [6].

Design courses are distinguished from engineering analysis courses by differences in pedagogy [4], format, and organization; see reviews in [2–4]. Dym et. al. [4] point out that unlike analysis courses which use convergent thinking, design also utilizes divergent thinking. In convergent thinking many different paths converge on a single correct answer. Divergent thinking, in contrast, focuses on the manipulation of concepts to allow new directions of inquiry. Recently ideas on teaching divergent thinking have been adopted into the classroom [8] and tools to measure the impact of divergent thinking have been developed [9]. While the concept of divergent thinking is valuable in a broad, epistemological sense, at a heuristic level it is evidenced by an ability to think in a framework of engineering systems and make decisions [4]. Thus activities in system thinking [10] and decision-making support divergent thinking. In Bloom's Taxonomy [11], decision making (i.e.

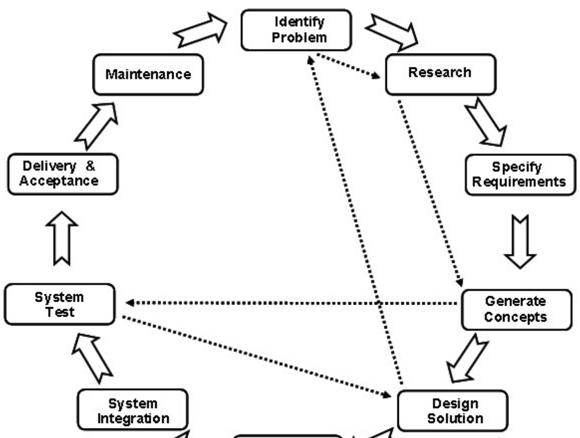

Fig. 1. The sequential ten step design process presented, with variations, in most undergraduate design textbooks.

evaluation) is the most advanced tier of learning so undergraduate students may have difficulty mastering this skill. To support systems thinking Dym [4] suggests specific 'habits of mind' including viewing design in a systems context, handling uncertainty, estimation, and performing experiments to clarify unknowns. Project-based learning [12] also gives students skills in applying divergent thinking.

Another difference between analysis and design courses is the importance of tacit knowledge in the design process [13]. Tacit knowledge can't be codified or transmitted in a form other than working closely and in person with an expert [14]. An excellent case study of tacit knowledge and the time required to master certain skills is reported in [15].

A large body of work on how students develop 'design ability' has found that student engineers construct knowledge of design in a social context that includes a wide range of perspectives [4, 16]. Design ability is intimately connected with use of 'design language' and developing, then internalizing, frameworks of thinking that support design. Students develop these frameworks by interactions with peers and experts. While research in this field is still on-going, one key to developing such frameworks is reflective practice. For a reflective practitioner of design '*knowing is not only rational and cognitive but also embodied in action and . . . reflection is critical to practice*' [17]. In other words, design involves questioning choices as well as making them. Experienced designers spend more time transforming and refining their understanding of a problem and transition quickly between steps in the design process [17]. An example of such transitioning is illustrated by the dashed arrow in Fig. 1 where an engineer realizes an error in their proposed design, returns to research solutions, generates new ideas, tests these ideas, and returns to the design task.

To apply research on design learning to course creation it was necessary to first determine constraints and set course goals. Constraints included student preparation, needs of the degree program, and beliefs and pedagogical knowledge of the instructor. Three factors impacted students' preparation for design. First, the engineering program at OSU focuses primarily on analysis. Second, due to a range of specializations in the program, students' ability to take classes at a separate campus, and wide variation in time-to-degree students have significant differences in prior knowledge. Third, while students have little formal instruction in design, most have encountered several in-depth projects with elements of teamwork. A key need of the degree program was meeting ABET Criterion 3 outcomes c (design), d (teamwork), e (problem solving), g (communication), and k (tools for practice) [7]. Additionally system design was identified by ECE's advisory board as critical for graduates. The course instructor had significant prior experience in active and project-based learning, and believed in the efficacy of these techniques for instruction [18, 19].

The research phase concluded by developing a set of project goals that were broadly categorized into direct and indirect learning outcomes. Direct goals can be taught using standard pedagogy, i.e. teaching students the process of design [6]. Indirect goals focus on changes to student's beliefs, motivation, and outlook which result from experience. In brief, while direct outcomes can be taught, indirect outcomes serve as evidence a design experience was developmentally *transformative*.

Direct goals were to teach the cyclical process of design along with techniques to organize and manage progression through the design process [6]. Examples are techniques for functional decomposition and time and resource management. To address ABET outcomes, students created a complex engineering system as part an organized team that had well-defined individual responsibilities. Teamwork was supported by integrating elements of effective teamwork and team building [20]. The final direct goal was preparing students with skills they need for the subsequent, independent capstone course.

An indirect goal was to give students the opportunity to develop a personal identity [21] by choosing roles [22] that fit their own conception of engineering. A related goal was to become accepted and empowered as a member of a local community of designers. The sense of empowerment and community was hypothesized to increase students' success in the second capstone course. A third indirect goal was for students to develop maturity in functioning on a team by being able to give, receive, and reflect on constructive criticism of their performance. Finally the course attempted to teach students that design is an 'art' as well as a science through which an individual's creativity can be expressed.

3. MODELING THE DESIGN COURSE

The research into design learning, discussed above, was used in developing a model of the course that supported the learning goals. The course model served to guide implementation. Three elements of design learning were integrated in the course model. The three elements are: the design process found in most design textbooks, the procedure of functional decomposition, and the Vygotsky cycle that describes how students socially construct knowledge. Each of these elements is described below followed by a discussion of how they were integrated. It is worth reiterating that while the linear flow of a journal article gives the impression the course design proceeded in a sequential fashion, in reality several iterations were required to arrive at the model described in this section. The instructor first taught the course in Spring 2005 and the course model described here was finalized in Fall 2007.

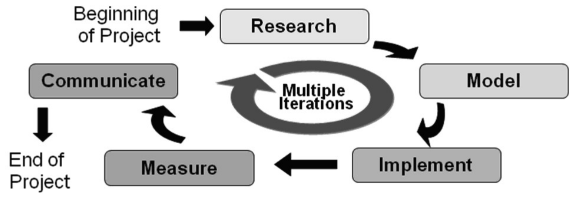

Fig. 2. The simplified, five step design process used for development of the design course and in the design taxonomy used to measure student preparation.

3.1 The design process

The course model was constrained by the need for students to complete a design project within the fifteen week semester. The ten step design process given in most engineering design books [6], Fig. 1, was shortened to a five step design process, Fig. 2. The first three steps of Fig. 1—identifying the problem, research, and specifying requirements—form the *research* stage of Fig. 2. The steps of generating concepts and designing a solution form the *model* step, while the construct and integration steps became *implement*. Due to the importance and time required for debugging the test step remained singular- *measure* in Fig. 2. The final step in the process is *communicate*, representing the delivery and acceptance stages of the original design process. Maintenance, while an important element of design, was included indirectly through project evaluation rubrics. It should be noted that in this course students produce a design product, not a design proposal; thus the proposal generation steps reported by Atman [16, 17] are subsumed in the research and model steps of the process in Fig. 2.

To better define each step of the design process, a design taxonomy [23] modeled on Bloom's Taxonomy [11] was created that drew from previous work on engineering taxonomies [24]. The design taxonomy classifies the level of cognitive process for each step of the design process shown in Fig. 2. Rather than the six hierarchical levels used in Bloom's Taxonomy the two lowest levels of cognition—remember and understand—are combined as a single level, understanding. Similarly the two highest levels—synthesize and evaluate—are merged into a single level, design. The design taxonomy used in this study can be downloaded from the author's web site [25].

An on-line survey based on the design taxonomy was then created to determine students' preparation for each step of the design process (Fig. 2). Faculty rated the impact of student work on the final grade in their course(s) and the relative importance of each element of the cognitive process and knowledge dimensions to course outcomes. The survey was piloted with both computer and electrical engineering faculty. Following e-mail solicitations, the survey response rate was 67%. Survey analysis showed that students did little researching and were weak in testing and measuring. Although faculty reported communicating as important, little work was graded, particularly in the early years of the program. Students performed the most work on modeling/calculating. The survey indicates that explicit training in researching a design project and providing ample time for project testing and debugging needed to be built into the course. Although the survey indicated that students performed a fair amount of fabrication, further research into prerequisite courses showed that fabrication was done on breadboards; adequate for prototyping simple systems but impractical for complex systems.

3.2 Functional decomposition

Functional decomposition is the process of dividing a complex problem into manageable pieces. The result of functional decomposition is a block diagram or system representation based on the function performed by each unit. Functional decomposition serves here as a necessary step in project definition and a mechanism to support effective teamwork [20]. The first step in the design project thus called 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. The blocks designed by individual students were integrated later in the project.

3.3 The Vygotsky cycle

A cyclic model of learning, the Vygotsky cycle, was used to develop procedures to teach design. In the Vygotsky cycle—initially proposed by Rom Harré [26] and refined by Gavelek and Raphael [27] —an individual's knowledge is constructed both internally from past learning and experience and externally by interaction with others in a cultural milieu. The Vygotsky cycle has received recent interest as a model of learning in literacy, art, education, and languages [28]; fields which require divergent thinking and making value judgments based on imperfect information [4]. There has been some work adapting the Vygotsky cycle to engineering education [29]. Other engineering learning cycles are similar to that proposed by Vygotsky, for example the VaNTH Legacy Cycle [30]. The Vygotsky cycle, shown in Fig. 3, describes movement through a 'conceptual space' represented by Cartesian axes [26] that describe how individuals realize (horizontal axis) and display (vertical axis) personal attributes such as knowledge or emotion. 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 the Vygotsky cycle understanding develops in four sequential transitions between the quadrants of Fig. 3; the literature does not discuss the time required for, nor the overlap of these steps. The transitions are:

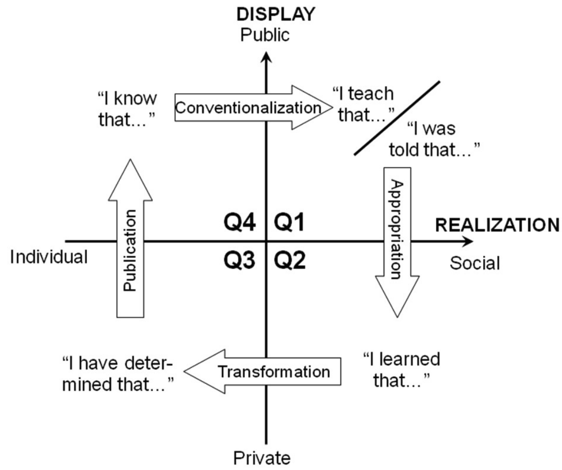

Fig. 3. The four quadrants of the socio-constructivist Vygotsky cycle. The arrows represent the transitions between quadrants and the text how students represent their knowledge at each step of the cycle.

- Appropriation: In quadrant one an individual is given information in a public, social setting (i.e. classroom) then *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 appropriated, a *transformation* occurs that acts both on the ideas and the individual. This transformation moves the student 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 step; faculty are familiar with students who can parrot back what they learned in class but do not seem to have wrestled with developing their own understanding of ideas.
- Publication: Since an individual's private conceptions of knowledge are not necessarily correct (i.e. a mis-conception) or do not match the accepted understanding of the cultural group, for affirmation the individual must *publish* their conceptions to others. By public display of an individual conception (realization) the student moves from quadrant three ('I *think* this true') to quadrant four ('I *affirm* this is true'). The act of publication tests the individual's understanding and affirms that their conceptions agree with those of the culture.
- Conventionalization: When the individual's learning is fully integrated back into the public social domain, they move from quadrant 4 back to quadrant 1; 'I *share* this truth with others of my culture'. At this point the student is a member of the community of designers and becomes, if desired, a teacher.

Fundamental to the Vygotsky cycle is the idea of transformation *both* of self and of knowledge [31]. The Vygotsky cycle's emphasis on social development also addresses aspects of teamwork and individual accountability, critical to well-functioning teams [20].

3.4 Putting it all together

The design process of Figs 1 and 2 is both iterative *and* sequential. Design is sequential since a lack of comprehension in early phases of the design process results in a sharply reduced probability of success in subsequent phases. Research on how students learn design [17] shows that experts spend more time on problem definition and transition more frequently between different stages of the design process. Thus students who bypass the early stages of the design process may have more difficulty making the rapid transitions observed in experts. Design is also iterative since solutions need to be tried, rejected, and rethought [4]. Developing expert behavior through problem modeling and iterative solutions is more successful than teaching students how experts solve problems [2]. Given the sequential/iterative nature of design, the course model needed to ensure students achieved some degree of mastery at each step of the design process before progressing to the next stage.

Achieving sufficient depth of learning was accomplished by integrating all three elements—the Vygotsky cycle, the design process, and functional decomposition—for both individuals and teams as illustrated schematically in Fig. 4. As teams go through the design process functional decomposition techniques are used help them to complete the Vygotsky cycle. Teams first *appropriate* their project by taking ownership and defining team goals. By using functional decomposition to assign parts of the project to individuals the team goes through the step of *transformation.* Blocks of the project become the responsibility of individual members who work to achieve functionality and meet design constraints for their block.

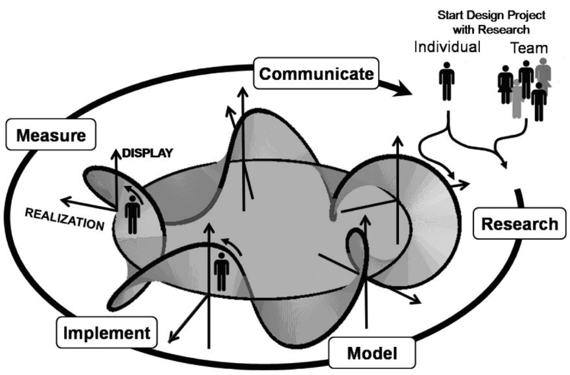

Fig. 4. Comparison of team's and individual's design learning obtained by merging the design process with the Vygotsky spiral. Individuals complete one rotation through the display and realization axes at each step of the design process students, while teams complete the process and Vygotsky cycle once.

Publication occurs when individual blocks are integrated into a functional system and blocks that don't work are redesigned. Finally the team goes through *conventionalization* by demonstrating their project. Each of these steps is supported by the course structure, assignments, and deadlines.

A similar cycle is followed by individual students, but rather than complete a single iteration of the Vygotsky cycle as they move through the five step design process, they complete the Vygotsky cycle (a 360° rotation through the display and realization axes) for *each* step of the design process. Thus by the time an individual completes the project they complete the Vygotsky cycle five times. An individual student's learning trajectory can thus be thought of as a 'Vygotsky spiral' [27], displayed diagrammatically in Fig. 4. This 'spiral trajectory' of learning is the core idea of this paper describing application of theory to the capstone design course. By completing the Vygotsky cycle (Fig. 3) for each step of the design process (Fig. 2), there is a better chance that students will master each step of the process and thus successfully conclude the design project.

To implement the Vygotsky spiral the course provided opportunities for public discussions, private/reflective learning, and regular presentation or publication of results at each step of the design process. The design project followed the five step design process with each step nominally two weeks in length. In each step learning activities were determined by the Vygotsky cycle, using the structure outlined below:

- *Quadrant 1:* The cycle starts in the public, social setting of the classroom using lectures, readings, and active learning to inform students of the goals, deliverables, and background of the current design process stage of their project.
- *Appropriation* is accomplished through formal team meetings. The block diagram guides how teams sub-divide the effort and assign tasks to individuals.
- *Quadrant 2:* At the meeting individual students negotiate their deliverables for the current stage of the design process, accepting the team (social) realization of the project.
- *Transformation:* Each individual on the team translates the team's needs to a set of actions by which they can accomplish their individual assignment.
- *Quadrant 3:* Each student works to master the tasks related to their block(s) of the overall team project, seeking help as needed.
- *Publication:* When the task is completed each student formally presents their work to the TA who scores the results using a rubric. If the score indicates the quality of the work could jeopardize the project, the work is not accepted. Guided by this feedback, the student continues to work on the task until an acceptable level of mastery is reached.
- *Quadrant 4:* On successfully completing their

individual portion, the student merges their design work and expertise with that of the team.

- *Conventionalization:* Each student's blocks are integrated into the overall team project and project documentation and design proceeds to the next step of the design process.

While many engineers have difficulty reconciling the idea of 'social construction of knowledge' with technical design, the Vygotsky cycle simply describes the learning process of engineers and engineering teams. As the design process of Fig. 2 determines the sequence of design activities and functional decomposition structures team and individual work, the Vygotsky cycle describes the learning process individuals and teams go through. As stated in reference [27] '*Through this movement, an individual's cognitive structures (i.e., schemas) and processes emerge from, but are not reducible to, his or her interactions with others.*' Thus conceptions of design (i.e. schemas), like a product design itself; emerge from going through a structured design experience. The active engagement and peer discussions inherent to socio-constructivism support the indirect goal of creating a 'transformative' experience.

4. IMPLEMENTING A DESIGN COURSE FROM THE MODEL

Once the course model was developed, the next step was to implement the model in the classroom. Since the specific implementation details are highly program specific, this section places the course in a curricular context, provides a course timeline, and discusses three design constraints: financial and equipment resources; human resources and time management; and the learning environment. Specific implementation details can be found in [32].

The design course is the first of two required capstone courses taken by senior students, and is three credit hours of the 125 hour program. Course enrollment varied widely over the period reported, from eleven to nearly fifty students. Students have a broad background in electrical engineering, having taken all but one required ECE course. One hour of classroom instruction and four hours of laboratory work per week ensured teams could schedule time together to meet and work on design projects.

The modeling phase of the course design project determined the teaching methods, sequential steps of the design project, the steps students needed additional instruction in, and how to develop mastery at each step. From this information a week-by-week timeline was developed, Fig. 5. The course timeline has three stages: a training phase, the design project, and reflection and reporting.

The six week training stage provides teamwork experience and teaches electronic device fabrication, ensuring each team member can contribute meaningfully to projects. Each student masters at least two fabrication or test and measurement skills (inset to Fig. 5); all skills are represented on the team. To let students apply skills, each team fabricates a working electronic device from a schematic diagram. Peer evaluation [33] at two points during this phase aids team development [20]. In summary, the six week training phase develops skills for the subsequent design project and moves teams through the forming and storming phases of team development.

In the second stage teams design an electronic device that will be integrated into a larger system. The design project follows the five steps of the design process (Fig. 4). Two iterations of the integrate and measure steps are necessary to enable redesign of blocks that could not be integrated into the system. For each step in the design process students completed the Vygotsky cycle of appropriation, transformation, publication, and conventionalization.

The final stage, reflection and reporting, gives students experience in technical communication and encourages reflection on how the experience was transformative. To conclude the project teams submit a technical data sheet, make an informal demonstration during a department-wide open

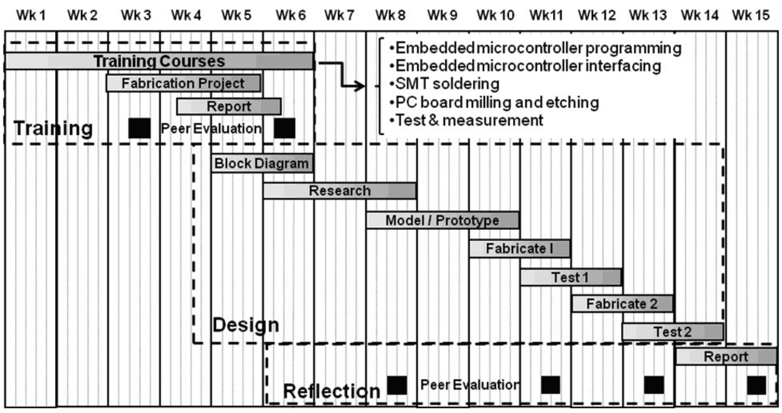

Fig. 5. Course timeline showing the training, design, and reflection phases. Each of the horizontal bars corresponds to graded work submitted by individual students and/or teams.

house, and create an electronic project archive on the university's information management system. Written responses to a series of open-ended questions allow each student to reflect on the design experience, this will be discussed subsequently.

Two constraints during course implementation were the available equipment resources and the cost of electronic components and materials. Traditional, fully-equipped lab benches were eliminated due to limited departmental resources and a 'bare-bench' model was used, discussed below. A student complaint from the earlier iteration of the design course was the large out-of-pocket expenses for electronic components. To improve student attitudes while controlling recurring costs, one set of components for the prototyping and integration phases of their design project were provided at no cost. Any replacement or substitution of components was at the students' expense.

Another critical factor for success of the course model was managing human resources. Key issues were finding teaching assistants (TAs) with sufficient experience to mentor students and managing student, and TA instructor time commitments. Four TAs supported both the first and second capstone courses; each TA worked nominally ten hours per week. TA's were recruited from graduate students who had taken the design course as undergraduates. TA responsibilities were broadly divided into technical and student support. Technical support included maintaining and managing the facility, developing future design projects, and expanding the range of design projects that could be supported. Student support included training students in fabrication and measurement techniques, answering questions, evaluation and grading, and working one-on-one with students when required. Due to the broad range of open-ended problems encountered in design, student support often took time away from technical support. By scheduling five hours per week for student support and five hours for technical support TAs were available four afternoons per week to answer student questions.

During the first iterations of the course lack of communication between TAs, the instructor, and students negatively impacted learning. The most effective of the methods tried to minimize miscommunication was to have each team select a project manager who served as a liaison between the team and the TAs and instructor. The project manager's grade, determined independently of peers, depended on collecting and archiving information, managing resources, and project organization. The project manager attended weekly meetings with the instructor and TAs, providing formal status reports and identifying potential problems with the team's project early in the design process.

As the Japanese proverb so aptly states: 'It is not just the mountain ahead, but the grain of sand in your shoe that wears you down.' To create an environment that maximized facility availability and support for individual students while minimizing maintenance issues the physical environment is styled as a 'Commons' with facilities shared and maintained by users. Training is offered in design-related skills as outlined previously; once users are certified they are able to access the facilities on an as-needed basis but also share in maintenance responsibilities. By emphasizing expertise and having users share in maintenance responsibilities the number of complaints about faulty equipment is minimal.

To give students twenty-four hour access to lab facilities a 'bare bench' model was adopted [19, 34]. In this model each team is assigned a 'bare' lab bench and is equips the bench from an on-line catalog. Two electronic catalogs, one for equipment and one for electronic components, give students access to a wide range of instrumentation and parts [35]. Teams, through their project manager, check out equipment for use for the duration of a project and are responsible for equipment they check out. The on-line equipment catalog eliminates student concerns about adequacy of instrumentation while the catalog with electronic components gives students access to a wide variety of parts they can use in their designs. The catalog system also simplifies inventory tracking and provides data on the use of electronic parts.

Overall, while the actual implementation of the course was time consuming, the theoretical framework and model outlined in the previous sections provided clear guidelines for making implementation decisions. Key issues were supporting learning at each step of the design process, maximizing opportunities for students to interact with each other and TAs, establishing clear channels of communication, engaging students facility upkeep, and giving students as much freedom as practicable.

5. MEASURING IMPACT

With any design project once a system is researched, modeled, and implemented the key question is 'does it work?' Assessing design learning is not straightforward, and there is wide variation in how capstone courses are evaluated [36]. This project used qualitative and quantitative metrics to provide insight into student learning at different stages of the design process. The results of evaluation summarized in this section include student artifacts scored using a rubric, reflective writing assignments, a summative examination, and peer evaluations. The course was first taught in Spring 2005 and underwent continual, iterative improvements until Fall 2007. The data presented is from Fall 2007 to Spring 2009. Due to minor changes to the course structure over this time data sets were analyzed by semester, reducing the statistical power. The iterative changes made it difficult to create a rigorous pre-post experimental design so quantitative measures only provide insight into student learning when they are compared longitudinally during a semester.

A closed-book summative examination given after the research phase of the project evaluated how well students learned system design and functional decomposition [37]. To measure how well students can technically represent their own and their team's work, the exam had students describe their team's overall system using a block diagram, the function of blocks, and how blocks were interconnected. Thus some answers on the test were common to the team while others reflected each student's design. Examination problems were scored by the instructor and TAs; at least three people scored each problem. Analysis of four semesters of examination problems indicates that most students are competent at representing their work and their team's work using a block diagram. The close resemblance of exam answers to the team's block diagram indicates that students carefully study the block diagrams for the exam thus supporting systems thinking. Students generally score highest at representing their project and explaining functions of blocks, but do less well at describing interconnections between functional units; the difference in scores is not significant (p-value = 0.15). Students did, however, score significantly (p-value < 0.05) less well on questions which asked them to place their work in the context of a larger system.

An online, electronic peer-evaluation system [33] was used to collect data on team performance twice in the first project and approximately every two weeks during the second project [38]. The peer evaluation system consists of separate evaluation modules that include a rating of team member attitude and value, the perceived work put forth by team members, open-ended text feedback to team members, and a rating of overall effectiveness. After completing peer evaluations students were able to view their cumulative scores, ranking within the team, and anonymous feedback from peers.

By correlating quantitative responses between different elements of the peer evaluation it was found that students judge peers by personal attributes on the first project and by the work performed in the second project. While it is not possible to show causation, we hypothesize that while perceptions, attitudes, and values play a large role in how students evaluate peers throughout a design project, actual contributions gain increasing weight as students become more experienced at design. Students who are novices at engineering design lack a frame of reference to evaluate peers and thus use personal attributes. Another observation was that during the second project the ratings students gave were negatively correlated with the ratings they received. In other words, students who rate peers *lower* on personal attributes are themselves rated *higher* by their peers. Similarly students who are perceived as doing a large amount of work tend to give lower scores with a larger distribution of scores. These results agree with other studies [39] that found less competent individuals were less adept at using available information to judge their own or others' performances. Peer evaluations, supported by qualitative evaluation, also showed that while students get better at judging engineering work in the design course, most students cannot distinguish effort from results.

Qualitative evaluation of the open-ended feedback students gave peers indicated several differences between the first and second projects. Significantly more students made comments about the value of specialized or design-specific knowledge on the second peer evaluation. This effect may be partially due to the differences between the two projects. Additionally while the overall amount of positive feedback given to peers was similar on both projects, in the second project praise was much more likely to be directed at specific skills, abilities, or knowledge rather than simply 'good job'. There were significantly more comments about students' leadership abilities and the value placed on leadership on the design project; which again may partially reflect differences between the projects. Perhaps most interesting was the way the word 'design' was used in providing feedback to peers. While students commented on design with the same frequency, the word was used primarily as a noun in the first peer evaluations—i.e. 'find problems with the design'—and as verb in the second evaluation—'he also designed the IR block' [16, 17].

To better understand how the design course was perceived by students and determine how the course achieved the indirect goals, a reflective writing assignment was given to students at the end of each semester. Students wrote 200 to 500 words each for four different topics: team organization, satisfaction with the student's role on the team, changes to their view of engineering that resulted from the class, and ethics and professionalism. No pre-course statements were solicited from students. Results were analyzed using grounded theory [40] to find fundamental changes in students' conception of design by first using TextStat for open coding, then doing additional analysis to identify several recurring sub-themes that gave insight into how the course impacted students. The sub-themes that ran through the reflective statements provided evidence that the theoretical framework on which the course was based had a positive impact on student learning:

- Students made clear distinctions between the creative work of design and the more procedurally oriented fabrication and testing indicating the socio-constructivist Vygotsky spiral clarified distinctions between design process steps. While students gravitated to different roles, they saw the roles as closely connected. There were some indications that design roles had higher status, but students in both roles commented on the value of others reviewing and checking their work. A common statement was the difficulty of dividing work fairly between students.

- Functional decomposition and the individualistic nature of quadrant three effort in the Vygotsky cycle succeeded in having students take ownership of the blocks they were assigned to design. A distinction was made between individuals' work and that done 'for the team'. Many of the fabrication steps, even when performed by an individual, were seen as part of the team's work while the work of completing block designs was viewed as an individual responsibility. While students had little sympathy for team members who could not contribute substantially to aspects of the project that were in the design domain, difficulties in fabrication were more easily forgiven.
- Another theme echoed by students was the importance of research and communication to later success in the design process. Interestingly, these steps of the design process are those least emphasized in the rest of the curriculum according to the survey discussed previously, providing evidence of the impact of the Vygotsky cycle. Many students stated that more time spent in research would have saved a significant amount of effort. Students frequently highlighted examples of ways failures in communication within the team or between team members and TAs negatively impacted their project.
- Issues with effective time and effort management were repeated throughout reflective statements. Although teams employed project management tools such as Gantt charts and work breakdown structures, the consensus was that students did yet have sufficient experience to accurately judge either difficulty or time commitments, particularly early in the project. Students often mentioned particular issues they would fix in future design experiences. The importance of organization was second only to communication to ensure the design process went smoothly.
- Students repeatedly referred to stages or steps in the design project. They rarely formally named the stages of design, rather separating projects more generally into categories of thinking (researching and modeling) and doing (implementing and measuring). Of those students who expressed a preference, more stated they preferred work related to doing, but a sizable minority preferred the researching and modeling phases of the design project. These statements provide evidence that the socio-constructivist framework of the course helped students distinguish different aspects of design, even though the formal language of the process was not used by students.

To measure project success rates, rubrics were used to determine if the project met stated design constraints. While project success rates are highly subjective as a measure of student learning, a working design project is in some ways the ultimate indicator of success, particularly to students. The scoring rubric measured how well the project functioned, the quality and robustness of the final project, how well individual functional units were integrated, and the team's understanding of their project. The instructor and TAs independently scored projects then discussed scores to arrive at a consensus rating. Over the last four semesters approximately one team in eight failed to get the design project working by the end of the semester, and the overall rubric-based score is approximately 85 on a 100 point scale, an acceptable outcome given the complexity of the design projects.

Two changes to the course led to significant increases in project success rate as determined by rubric scores. One is creating the position of a student project manager on the second design project. Providing students with a formal procedure for project construction on the first fabrication project also decreased the number of iterations required to get the fabrication project working from three to very close to one. The step-by-step guide lays out each stage of the design and requires a team member not involved in a given process step to check the team's work.

6. CONCLUSIONS AND IMPACT ON PRACTICE

It has been argued that traditional, analysis-based programs do not fully prepare students to engage in engineering design [1]. This article outlined how a socio-constructivist learning model, the Vygotsky cycle, was applied to a design course that addressed both direct and indirect learning goals. The Vygotsky cycle provides insight into practical ways to support design learning for both teams and individuals. Teams use formal project management techniques to assign responsibilities to individuals, integrate individual contributions into a larger system, and present the results of their work. Individuals need to be given learning opportunities that allow them to sequentially master each step of the design process so they can rapidly move between steps on successive iterations [17].

A three step model was used to apply the broad insights from theory to implementation of a design course. By classifying design learning using a taxonomy [23], the course was able to address deficiencies in student preparation through an electronic fabrication project. In the second, design project step the Vygotsky cycle [26] was integrated with the design process and functional decomposition [6] to support team and individual learning. Each individual went through the Vygotsky spiral [27], Fig. 4, five times in mastering each step of the design process. Teams concluded the project with communication of results in several formats and reflection on how they course impacted their conceptions of engineering design.

Qualitative and quantitative evaluation showed the 'Vygotsky spiral' model met the direct learning goals outlined in the research phase of course design. Students' reflective statements referred to stages of the design process. Students recognized the importance of organization, management, and leadership to the design process, and project success rates improved after formally implementing a project manager position on each team. Students understood the role of functional decomposition in system design as reflected on their performance on a summative 'block diagram test' and made repeated references to the process of project decomposition. Few students, however, showed mastery of the interconnections between blocks or placing their project in a larger context. The course improved students' ability to function on a team and while the way they evaluated peers changed, they still mistook effort for results. Finally reflective statements by students showed some evidence that the course model supported divergent thinking [4], but no direct measure of the degree of divergent thinking was performed [9]. A direction of future work is to develop teaching or evaluation methods that allow students to distinguish between the effort put in by peers and the results they achieve.

Themes from reflective statements provided some evidence the model enabled the indirect goals. One of the clear themes that emerged from reflective statements is that students developed identities around the roles they took on during the project. It would be worth investigating why some roles (i.e. designing) were seen as having more status than others (i.e. building). Students also reported significant gains in design ability and were prepared to engage in the second, independent capstone course. The sense of ownership of technologies and processes that emerged gives evidence they feel empowered, at least in the design roles they took on. No evidence emerged, however, that students saw the process of design as creative; creativity was rarely mentioned in reflective statements.

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Alan Cheville received a BS degree in 1986 and Ph.D. degree in 1994 both in electrical engineering from Rice University in Houston, Texas. His doctoral work covered a broad range of topics in ultrafast optical spectroscopy, focusing primarily on 'Buckyballs' or carbon-60 molecules. Currently Dr. Cheville is an associate professor in the Department of Electrical and Computer Engineering at Oklahoma State University and divides his time between teaching, research in optoelectronics, and engineering education. In the field of optoelectonics, Dr. Cheville specializes in ultrafast THz spectroscopy and imaging, particularly for sensing applications.

In engineering education Dr. Cheville leads an NSF-sponsored departmental level reform project—*Engineering Students for the 21st Century*—that is introducing contextualized design problems throughout the curriculum. Focusing on undergraduates, this project is aligning the behaviors that are taught in the degree program with those that help students succeed in engineering profession. Dr. Cheville is also interested in investigating alternative approaches to androgogy and degree programs. Dr. Cheville is a member of the IEEE, ASEE, and the Optical Society of America.