AC 2007-2024: CONVERGING-DIVERGING DESIGN STRATEGIES IN A SOPHOMORE LEVEL DESIGN SEQUENCE: REVIEW OF AN ELECTROMECHANICAL PROJECT

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Converging-Diverging Design Strategies in a Sophomore Level Design Sequence: Review of an Electromechanical Project

Abstract

At our university *Sophomore Clinics* I and II are part of an eight-semester design sequence in which students progress from basic data collection and reverse engineering projects through more open-ended, industry-sponsored capstone design experiences. The team of multidisciplinary faculty from Engineering and Communications who teach the sophomore level courses have observed the difficulty students have tackling the fundamental open-ended nature of true design problems and have subsequently revised the sequence. For the Fall of 2005 the Sophomore Clinic sequence was revised to introduce Dym *et al.'s* converging-diverging framework for design by incorporating a series of three projects of increasing complexity with accompany activities designed to reinforce the converging-diverging concepts. For the third project in the series, roughly sixty students participated in an open-ended electromechanical design project that included lectures and activities to reinforce the design framework, assessment of the retention/comprehension of the framework's concepts, and a final design competition. While assessment data was unable to show a correlation between comprehension of the design framework and improvements in students' designs, results do show that students had adequate retention/comprehension of the converging-diverging philosophy and that students' designs performed better in the competition following the revised course as compared to the previous year.

Introduction

All students in the engineering curriculum at our university are required to take an eight-semester design sequence called the *Engineering Clinics* that moves from closed to more open-ended problems. The sophomore year of the Engineering Clinic series is a team taught course devoted to design and communication. The students spend 160 minutes in a single engineering lab section and 150 minutes in three communication sections per week. The course is taught by faculty from multiple departments within the College of Engineering and the College of

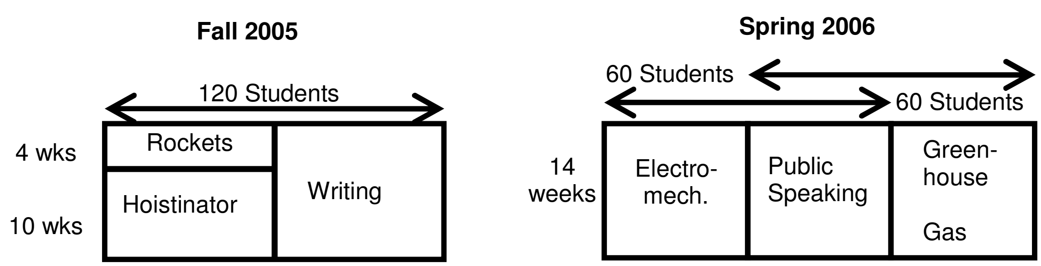

Figure 1: Restructured sophomore design sequence beginning in fall 2005. The fall semester was divided into one four-week project and one ten-week project. Students could choose between semester-long electromechanical design projects or greenhouse gas projects in the spring. Students enrolled in communication courses concurrently during both semesters.

Communication. Assignments and grading are integrated through both communication- and engineering-specific sections, a trend which began gaining national acceptance[1,2,3] nearly a decade ago. In previous years the Sophomore Clinic has tasked students with various semester-long projects including the design and construction of residential bridges, music effects pedals, golf ball launchers, motorized cranes, and load-bearing truss systems. While these projects were successful at following the national trend of integrating design into the curriculum at this early stage [4,5,6,7,8] they were not as successful in *teaching* students to be good designers. This observation was driven by the difficulties students had with more open-ended design problems in Sophomore Clinic II, the second half of the sophomore level sequence.

Evaluation
Synthesis
Analysis
Application
Comprehension
Knowledge

Figure 2: To reinforce critical thinking about the design process, components of the fall projects were discussed according to levels in Bloom's Taxonomy.

In the 2005 offering of the Sophomore Clinic sequence, the instructors revised the course to introduce a more structured approach to teaching design. In previous years, a single, semester- long project was used in both the fall and the spring. In the new structure, students are given a well defined, well constrained problem during the first four weeks of the fall course (the Bottle Rockets Project[9]), followed by a more open-ended 10 week design problem with fewer constraints (the Hoistinator [10]), shown in Figure 1. For the following spring semester, roughly half the students work on a very open-ended electromechanical project while half work on a greenhouse gas reduction project[11]. The three projects of increasing complexity are used to introduce a framework for approaching design problems. It is intended that this progression will enable the students to be more conscious and therefore more capable of the processes that effective design teams undergo.

This paper focuses on the restructuring of Sophomore Clinic II for the spring 2006 semester. It begins with a discussion of the converging-diverging framework adopted for the fall-spring sophomore sequence, briefly recaps students' exposure to the methodology in the fall, and then details the incorporation of the new framework in the context of the spring's electromechanical project. Preliminary assessment methods and results are discussed. Assessment is meant to test two hypotheses:

- did the restructuring of the sequence lead to students' comprehension of the concepts of converging-diverging design, and
- does students' facility with converging-diverging design concepts lead to better designs in the electromechanical project.

Functionally, the two main changes to the spring course were in its structure and language. This combined focus on structure and language was shown by Dahm *et al*. to lead to improvement in outcomes of the Greenhouse Gas section of Sophomore Clinic II[12] which supports its use here.

A framework for teaching design

In discussing student difficulty with design problems, Dym *et al.* link their struggle with open-ended problems to the difference between the "engineering science" model of engineering education, which views acquisition of analytical competency as foundational, and the "project based" model, which views active participation in learning experiences as foundational[13]. Most students are extremely practiced in the modes of learning associated with the engineering science model: they can readily perform mathematical and scientific analysis. However, simply placing them into a project based setting such as the engineering clinic sequence does not alter their thinking. As we saw, students continued to approach their work as though they were doing assigned homework problems. In fact, engineering design calls for a radically different way of utilizing mathematical and scientific analysis:

> *Engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints.*[13]

When mathematical and scientific analyses are practiced to achieve competency, the emphasis is on finding the right answers. When they are applied to engineering design, the emphasis is on the many higher order skills embodied in the above definition: *generating, evaluating, and specifying* ideas that meet human needs within various constraints. These levels of thinking reflect the top tiers of Bloom's Taxonomy (see Figure 2). The design process involves using the physical laws to guide the generation of design ideas which are then specified as design solutions, but must be subsequently evaluated, often using those very same physical laws. At every step, however, the designer should have in mind the question: How well does the design solution meet the design criteria?

Converging-diverging philosophy

To define what kinds of thinking are required to engage in engineering design and to shed light on how it might more effectively be taught, Dym *et al*. propose a framework they call Divergent-Convergent Thinking . In brief, the Diverging-Converging framework breaks the design process into two interrelated phases. Convergent Thinking uses the analytical skills learned in physics and mathematics courses—experimental methodologies and observations, for example, and other quantitative and qualitative methods to assess various design solutions. The results of these analyses and observations are then used to enhance subsequent design iterations. Divergent Thinking is used to generate initial design concepts and to widen the range of thinking

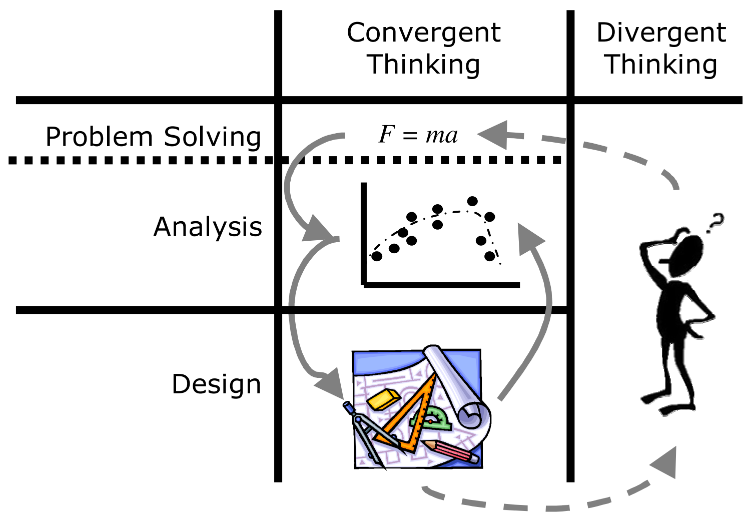

Figure 3: Schematic showing delineation between Convergent Thinking, Divergent Thinking, Problem Solving, Analysis, and Design. Divergent Thinking generates ideas which are evaluated using Convergent Thinking (Problem Solving and Analysis), and lead to improvements in the design solution.

when a particular design strategy has reached a road block. (Capitalization is used in this section to indicate specifically defined terminology.)

Our take on this work defined two pairs of mental arenas: Design vs. Analysis and Problem Solving, and Convergent vs. Divergent Thinking (see Figure 3). Within these arenas, during the fall 2005 semester we discussed Convergent Thinking as applied to Analysis/Problem Solving and to Design, separately, and we also discussed Divergent Thinking as applied to Design. These three concepts are discussed below.

In the Divergent Design phase, ideas are generated and recorded with almost no restrictions; ideas must be at least theoretically plausible given current technology. In course assignments related to the project, students were given this explanation:

> *Divergent thinking is contrary to convergent thinking in that the ideas/choices do not have to lead directly to the best solution and they do not have to necessarily fall within the constraints. It helps, though, if the ideas are technically feasible.*

The Divergent Design phase is most associated with brainstorming. Its importance lies in its ability to overcome design hurdles by, to use the cliché, thinking outside the box.

The ideas generated within the Divergent Design phase, though not necessarily bound by constraints, must still be analyzed to determine their efficacy. The Convergent Thinking aspect provides both a means of assessment of the choices made in the divergent phase and a rationale for making additional choices in order to find the optimal solution, a concept we introduced as Convergent Design. In our framework, Convergent Thinking was described for students as follows:

> *In brief, convergent thinking may be thought to include (a) the generation of constructive design ideas that work within the constraints and (b) analysis and problem solving that assesses a particular design's efficacy.*

Convergent Thinking, in our framework, involved Analysis and Problem Solving, which were separated along a thin line. Convergent Problem Solving was discussed as the textbook-type homework problems with which engineering students were most familiar. The problems are extremely well defined and constrained to the point that they offer, usually, a single correct answer. While this is not necessarily in line with a design problem, such textbook type problems highlight the link between engineering and design – engineers use the physical laws, chemistry, physics, etc. to solve problems in an effort to learn something about their designs. Convergent Analysis was discussed as the assessment of a particular design with respect to the given set of goals and criteria. Convergent Analysis, then is slightly more open-ended in that one must formulate the problem as well as apply the physical laws. With these definitions, however, there will invariably be some amount of overlap in the process.

The lynchpin in our approach was formalizing the link between Convergent Analysis/Problem Solving and Convergent Design as a means to refine design decisions and choices based on analytical work, experimentation and observation. The need for emphasis on this aspect of the process was clear. Previous design projects within Sophomore Clinic showed that while students were comfortable and performed well in the problem-solving and to a lesser degree the analysis phases of the project, they rarely linked results of this convergent analysis / problem solving with decisions/choices that would form the basis for convergent design. They remained "unaffected by their education" [14]. For example, a student developing a truss system for the fall project commented to the lead author that his calculations showed his truss could hold over 4 times the *maximum* weight limit but still asked if he should add more strengthening supports. During the spring 2005 electromechanical project students routinely chose initial designs at the outset of the semester and refused to rethink (let alone abandon) their designs even when it became evident that their designs were hindered by substantial functional limitations.

It was clear from these and other observations, that while students were engaged in the generation of ideas and the solution of problems, the two arenas were not used in a synergistic fashion to systematically improve design solutions. The remainder of the paper will outline the structure of the Sophomore Clinic II electromechanical project (design-related components) highlighting our incorporation of converging-diverging strategies, discuss assessment techniques used during the semester, and conclude with results and observations from the course.

Incorporation of design framework, course content and assessment

Roughly sixty students participated in the electromechanical project, the Overhead Crane, in spring 2006. In teams of six, students were tasked with designing and constructing motorized vehicles capable of traversing an aboveground electrified rail system while utilizing a winch and electromagnet to lift and move objects of varying mass. Renderings of the various components are given in Figure 4. Each team was divided into three task groups consisting of two members each: vehicle design, interface design, and electronics. This report deals primarily with the interface design group.

The course content included reverse engineering concepts, a review of the converging-diverging philosophy, focused design activities, midterm and final design presentations, a concluding design competition, and assessment at various stages. Assessment of students' retention of the converging-diverging framework from the previous semester began on the first day of class.

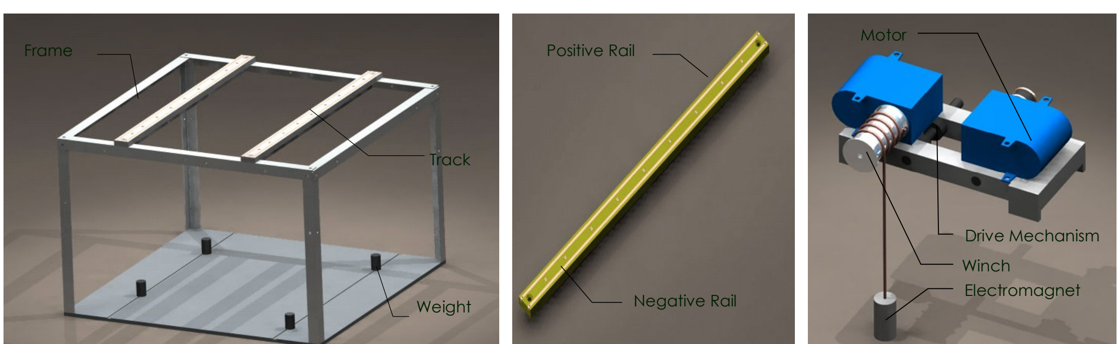

Figure 4: Prototype systems for electromechanical project in spring 2006. (a) Frame for vehicle, (b) powered rails, (c) prototype vehicle.

On the first day of the spring course, week one, students were surveyed (Learning Activity # 1, shown in Appendix 1) on their understanding and retention of the convergent-divergent design methods used in the previous semester. An in-class assignment, given to each team of six, asked three questions:

- Question #1: *If we think about the crane project in terms of a converging-diverging framework, what aspects of the project were* convergent design?

- Question #2: *If we think about the crane project in terms of a converging-diverging framework, what aspects of the project were* convergent problem solving*?*

- Question #3: *If we think about the crane project in terms of a converging-diverging framework, what aspects of the project were* divergent design*?*

Students responses were scored according to the keys located in the tables in Appendix 1 on a scale of 1 (lowest) to 5 (highest).

Next, Bloom's Taxonomy (see Figure 2) was discussed and the students were given the following question which was answered in class by each team of six.

- Question #4: *Give an example from either the bottle rocket project or the crane project that exemplifies each level of thinking.*

Student responses were graded on a scale of 0 to 6 where one point was awarded for every correct level. Students were questioned about Bloom's Taxonomy in order to use the scores as a reference value since Bloom's Taxonomy had been covered in previous semesters.

Directly after completing the assignment, students participated in a focused design activity to reinforce the concepts of divergent thinking. The activity involved building a "Rube Goldberg" device to blow out a candle. All construction materials used in either the Hoistinator or the Bottle Rocket project from the previous semester (foam board, duct tape, aluminum bar stock, nuts and bolts) were allowed. Students were also told they were *required* to use an aerosol can of whipped cream, a foam hammer, a bowling ball, and a live rodent. Students were given 20 minutes to design a device which they presented to the class.

During the following class period, week two, students working on the interface design task reverse-engineered commercial video game controllers from MadCatz, sketching the controllers and making basic circuit schematics for the system of buttons and switches used. The process emphasized convergent thinking through analysis/observation of the existing device.

In week three students were engaged in a discussion designed to introduce them to concepts involved in good interface design [15] which are given in Appendix 2. Students were tasked with assigning components of a car's dashboard to their most relevant interface heuristic. This assignment highlighted the evaluation aspect of convergent thinking by forcing students to assess a component with respect to the design criteria as laid out by the heuristics. For example, several students identified the clutch-brake-accelerator's left-to-right layout as an example of adherence to "consistency and standards" since it is virtually universal around the globe.

For the following four weeks, interface design teams were tasked with learning Solidworks (a 3D CAD package) and designing three different prototype interfaces to control their vehicles. At a minimum, their interfaces had to control the crane's forward/reverse motion, raising and lowering of the winch, and the on/off operation of the electromagnet. With these specifications students were tasked with brainstorming ideas (Divergent Thinking), drawing key features from each idea (Convergent Thinking, Analysis), and designing the physical interface and basic circuitry to achieve the desired functionality (Convergent Thinking, Problem Solving). In addition, student teams were given a set of "soft" criteria to be met, given in Table 1.

Table 1: Design review assessment criteria for each prototype

Item	Criteria	Description of Criteria, Rated from 1 (lowest) – 5 (highest)
1	Aesthetics	*Is the design visually appealing?*
2	Ergonomics	*Would the design be easy to hold, to manipulate, and to control?*
3	Visual Identity	*Do the buttons and switches convey their function visually?*
4	Extra Features	*What degree of functions is present beyond the basic movement and on/off requirements?*
5	Ease of Manufacture	*Would the interface be simple to manufacture?*
6	Originality	*How original is the design compared to existing videogame-like interfaces?*
7	Feasibility	*How strongly do you believe this design concept will work in reality?*
8	Overall Design	*Overall, how would you rate this design?*

During a mid-semester Design Review in week 8, each interface team presented their three prototypes, which were evaluated by engineering faculty as well as faculty and students from an upper-division Graphic Design class in the Art department. This assessment was used to evaluate the student team's ability as designers by evaluating their three prototypes against set criteria. All three designs for each team were graded individually against the criteria in Table 1. Scores of 1 (lowest) through 5 (highest) were given for each criteria. During the Design Review interface teams were also evaluated on the strength of their presentation, their proficiency with SolidWorks, and the dissimilarity of their designs. Table 2 lists the design-related criteria for which a team received a single grade based on all three designs ranging from 1 (lowest) to five

Table 2: Design review assessment criteria combining all three prototypes

Criteria*	Description of Criteria, Rated from 1 (lowest) – 5 (highest)
Dissimilarity	*How different are the three designs visually and/or functionally?*

* Interface design related criteria only

(highest).

The pedagogical goal of this semester was to teach students a process of design such they could maximize their scores in each category, which would then be taken as evidence of a good design solution. The mid-semester review was intended to serve as an assessment of their prototypes and hence their ability as designers. After the Design Reviews, students modified their designs based on recommendations by engineering and art faculty and art students before each design was printed on a 3D printer and assembled in weeks 9 – 13.

Table 3: Final design competition performance criteria

Criteria*	**Description of Criteria**
Meets minimum requirements	*The crane must move a minimum of one 100 gram ½ in. steel dowel pin a distance of 2 feet in two minutes.(scored as pass/fail)*

* Interface design related criteria only

The final competition was held during week 14 in three parts. In part 1, each team was required to move a minimum of one 100 gram, ½ in. piece of steel bar stock a distance of 2 feet in 2 minutes. In part two, the electromagnets for each overhead crane were tested for lifting capacity. In part three, a head-to-head competition, teams competed one-on-one to move as much mass as possible from one end of the three foot track to the other in two minutes. The interface design-related performance criteria for the final competition are given in Table 3. The "meets minimum requirements" criteria is the only design-related assessment available for the final designs from the 2006 course. A detailed assessment of the final designs, similar to the assessment during the design reviews, was not conducted but is planned for the 2007 teaching of the course.

Extrapolating to other design frameworks

At the core of the methods describe in this paper is the idea that students must not only be exposed to a design framework, but must also be capable of using it in their design processes. Consequently, the activities developed for this course were meant to reinforce the converging diverging philosophy. While this work has focused on a specific framework for approaching open-ended problems, several other frameworks exist. For example, Eide *et al.* propose a ten-step approach, which is taught in our Freshman Clinic course, that includes: Identification of a need, Problem definition, Search, Constraints, Criteria, Alternative solutions, Analysis, Decision, Specification, and Communication[16]. Concept reinforcing activities and assessment tools similar to those discussed in this work can be developed around this and other frameworks as well.

A key component of the concept reinforcing activities in this project was the incorporation specific activities to identify and to practice the various modes of thinking. Similar activities could be developed for design projects following the ten-step framework of Eide *et al.* For example, in past Sophomore Clinic courses we have given students products and tasked them with identifying the needs the products filled. This type of exercise mapped onto the lowest level of Eide *et al.'s* framework. Most design courses also include final project reports, competitions, or speeches that give students an exercise in Communication of their designs. Activities that practice the various steps in a framework, however, should be clearly linked to their place in the framework to promote the importance of the entire framework over the specific activity.

Assessment of students' ability to navigate a given design framework is important in closing the pedagogical loop. The ability to identify or to label where their specific activities fall within a given framework is a first start. This assessment should be carried out throughout the semester and should also include questions that reach higher on Bloom's Taxonomy such as evaluating another design team's labeling of the activities in their process.

Results

Table 4 shows the average scores across all teams from Learning Activity #1, which tested students' comprehension/retention of convergent divergent design methods, Questions 1 – 3, and their understanding of Bloom's Taxonomy, Question 4. Questions 1 – 3 were graded on a 1 (lowest) – 5 (highest) scale while question 4 was graded on a 0 (no levels correct) through 6 (all levels correct) scale. The average scores for the convergent-divergent items range from 3.7 through 4.1 out of 5 showing an adequate level of comprehension. Bloom's Taxonomy scores an average of 4.7/6 which shows an adequate class wide average comprehension.

Table 4: Average scores from learning activity #1 testing comprehension/retention of convergent-divergent design methods

Item	Design Concept	Score (1 – 5)	Std. Dev.
1	Convergent Design	*3.9*	*1.1*
2	Convergent Problem Solving	*4.1*	*0.5*
3	Divergent Design	*3.7*	*1.0*
4	Bloom's Taxonomy	*4.7 (out of 6)*	*0.57*

It is interesting to note that the standard deviations on Convergent Problem Solving and Bloom's Taxonomy questions were roughly half those of the Convergent Design and Divergent Design questions, 0.50 and 0.57 versus 1.1 and 1.0 respectively. This suggests validation of the premise that students are well versed in convergent Problem Solving and consequently are able to identify its use in a project. The results may also suggest that concepts which are covered over multiple semesters (such as Bloom's Taxonomy) will be less ambiguous to students; that is, as a cohort they tend to agree on their meaning and implementation.

Table 5: Combined average scores from learning activity #1

	Average	Std. Dev.
Average Convergent-Divergent Comprehension(Table 4 items 1 – 3)	*78.1%*	*16.9%*
Average Bloom's Taxonomy (Table 4 item 4)	*78.6%*	*9.4%*

Table 5 shows a percentage score for questions 1 – 3 weighted equally in the first row and the question 4 on Bloom's taxonomy in the second row. The former combined score, which will be called the Convergent-Divergent Comprehension, is meant to give an aggregate measure of students' comprehension of the converging-diverging framework. Bloom's Taxonomy was included since it is a concept which was taught in previous semesters to the students when they were freshmen. Equivalent levels of comprehension suggest that the convergent-divergent philosophy has been understood as least as well as that concept. However, the higher standard deviation in the convergent-divergent comprehension score suggest that the concept is not understood as broadly at the individual level; some students grasp the concept much better than others (which was seen anecdotally).

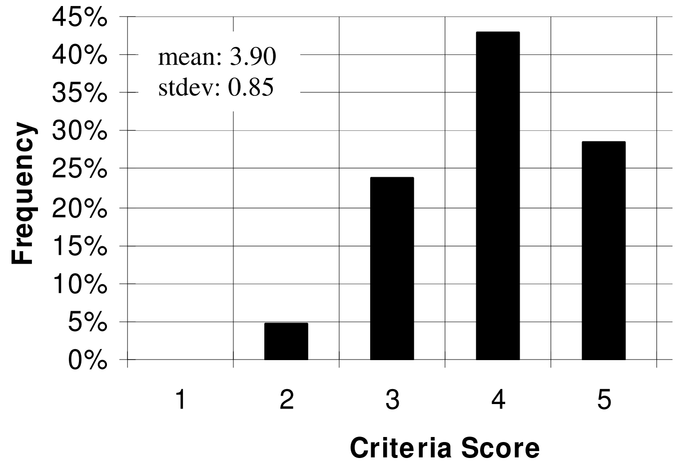

Figure 5: Histogram of scores on all questions from all teams for the learning activity in Week 1. The figure represents the overall distribution of retention/comprehension of the convergent-divergent approach taught the previous semester.

Figure 5 shows a distribution of scores on all questions 1- 3 from Learning Activity #1 across all teams. This representation is meant to give more insight to the distribution of understanding throughout the class. The distribution is clearly weighted toward the high end, 4 and 5 out of 5, with only a few outliers receiving scores of 2 and none receiving scores of 1.

Table 6: Art student's scores from mid-semester design reviews

	Team Number								**All Teams**	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Average**	**Std. Dev.**
Overall Design	*4.3*	*4.0*	*4.5*	*4.3*	*4.0*	*3.3*	*4.3*	*3.7*	*4.0*	*0.38*
Design Factors	*3.7*	*3.4*	*3.8*	*4.0*	*3.1*	*2.6*	*3.6*	*2.7*	*3.4*	*0.52*
Dissimilarity of Designs	*4.3*	*4.0*	*3.3*	*4.0*	*3.7*	*3.7*	*4.3*	*3.7*	*3.5*	*0.35*

Table 7: Art and engineering faculty's scores from mid-semester design reviews

	Team Number								**All Teams**	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Average**	**Std. Dev.**
Overall Design	*4.0*	*NG*	*4.0*	*NG*	*3.0*	*3.0*	*4.0*	*3.0*	*3.5*	*0.55*
Design Factors	*4.0*	*3.8*	*4.4*	*3.8*	*4.3*	*3.3*	*4.0*	*3.5*	*3.9*	*0.39*
Dissimilarity Of Designs	*5.0*	*5.0*	*4.5*	*4.0*	*4.5*	*5.0*	*5.0*	*3.5*	*4.6*	*0.56*

Tables 6 and 7 show the team scores from the mid-semester Design Reviews in three categories. The Overall Design category is taken directly from Table 3: Design Review Assessment Criteria, Individual Designs, item 8, while Design Factors is an average score of items 1-7 from the same table of review criteria. These scores for Overall Design and Design Factors in Tables 6 and 7 are from the prototype design with the highest Overall Design rating. The average scores show marginally adequate performance for the Overall Design and Design Factors categories ranging from 3.4 through 4.0 out of 5 which correspond to a range of 68% to 80% of full scale. There is also variation between faculty scores and student scores.

Table 8 shows R2 values of the linear correlations between a team's Convergent-Divergent Comprehension score and the Bloom's Taxonomy question score versus the Design Factors, Overall Design, and Dissimilarity of Design measures. The linear correlation is chosen as a basic measure of correlation. The column variables, concept competencies, represent the student's facility with the convergent-divergent framework and Bloom's Taxonomy, respectively. The row variables, design outcomes, represent measures of the student's best design (or of all three together for dissimilarity) as given by the average of the faculty and student ratings weighted equally. The table shows reasonable agreement between Overall Design and Bloom's Taxonomy, and less than adequate correlation between Design Factors and Bloom's Taxonomy. Only slight correlation exists between the converging-diverging concept competency measures and design outcomes measures. The data suggest that students who are more proficient with Bloom's Taxonomy likely produced better designs while better designs and comprehension of convergent-divergent concepts are only marginally related as measured by the assessment questions. Competency in convergent-divergent design concepts shows only slight correlation with dissimilarity of designs as well.

Table 8: Correlation coefficients (R^2) between learning activity #1 assessment questions and design review outcomes

	Convergent-Divergent Combined	**Bloom's Taxonomy**
Student + Faculty Dissimilarity of Designs	*0.27*	*0.00*
Student + Faculty Design Factor	*0.34*	*0.53*
Student + Faculty Overall Design	*0.44*	*0.81*

Table 9 shows the percent of teams that successfully completed minimum requirement for the spring 2005 and spring 2006 Overhead Crane competitions. The restructured spring 2006 course shows clear improvement in the number of designs successfully meeting the minimum requirements. However, this improvement cannot be directly attributed to the restructuring of the course.

Table 9: Percent of teams successful at meeting minimum requirements

	Spring 2005	Spring 2006
Meets minimum requirements*	58.3%	90%

*The interface performance criteria were too dissimilar between 2005 and 2006 for comparison.

Conclusions

The fall 2005 Sophomore Clinic I design course was restructured in order to incorporate concepts of convergent-divergent design frameworks. The new philosophy was taken largely from Dym *et al*.'s work which sees Convergent Thinking in two arenas, Analysis / Problem Solving and Design, that are used to evaluate a given design solution. The framework sees Divergent Thinking as a primarily design (brainstorming) related activity. The two ideas form a cycle of idea generation and evaluation that are used to move toward a final solution that meets all needs and satisfies all constraints (see Figures 3 and 4).

Roughly 60 students participating in the electromechanical project of the spring 2006 Sophomore Clinic II course were evaluated to assess how well the concepts of convergent-divergent design methods were comprehended and retained from the previous semester. Assessment carried out at the beginning of the course shows an average score of 78.6% (out of 100%) on a measure of student's comprehension/retention of convergent-divergent design methods covered in the previous semester (see Table 5). Concurrent assessment shows a 78.1% retention score on comprehension of Bloom's Taxonomy, a subject that the student saw in several previous semesters, for comparison (see Table 5). Together with the improvements in performance, this suggests that retention of convergent-divergent concepts is on par with retention of other material covered and that it therefore had entered the students' lexicon of thinking and may have had an effect on design outcomes. These results support our first hypothesis that the restructuring of the Sophomore Clinic sequence lead to students' retention/comprehension of converging-diverging design methods.

Assessment of mid-semester Design Reviews shows students' prototype designs fared only marginally well on measures of dissimilarity, design features, and overall design as measured by art students and art and engineering faculty (see Table 6). The student's designs received their best rating in Dissimilarity of Designs from faculty (4.6/5) and their lowest rating in Design Factors from art students (3.4/5).

Some correlation (R^2=0.81) is seen between comprehension of Bloom's Taxonomy and the quality of prototype designs (see Table 8). Improvement in measures of comprehension of the convergent-divergent design process and the quality of prototype designs presented at the mid-semester Design Reviews shows little or no correlation. This could have occurred for several reasons including students' lack of preparedness for the mid-semester reviews, students' failure to navigate the converging-diverging framework toward an effective design solution, and issues with the survey instrument used to assess the designs. The lack of preparedness argument stems from the class's average score of 78.6% on a measure of their level of preparation but is not considered a useful rationale. Assessment conducted at the beginning of the semester showed clear retention of the concepts of the converging-diverging framework which gives support to the argument that better understanding of the methods failed to translate into more effective designs. Issues with the survey instrument and its timing are another likely source of error. While detailed assessment of students' designs was carried out at the mid-semester reviews similarly detailed assessment was not conducted from that point forward nor was it repeated for the finalized designs.

Some improvement in gross measures of aggregate class performance were seen between the spring 2005 course offering the restructured 2006 course offering. Table 9 shows a 54% increase in the number of teams that successfully completed the minimum requirement for the project from 2005 to 2006 which broadly suggests success in producing better designers but does not link the improvement to students' facility with the converging-diverging framework. Even though correlations between improved designs and improved understanding of the convergent-divergent philosophy were not seen directly in the mid-semester Design Reviews, Table 4 still suggests that the concepts were retained by the students from the previous semester.

Given that students retained concepts of the converging-diverging framework, the overall success of the course, and Dahm *et al*.'s published success with the converging-diverging framework, the authors are lead to revisit our pedagogy and assessment methods for the spring 2007 teaching. Specifically, we have addressed our assessment instruments and their timing by surveying students individually (as opposed to in groups) throughout semester, by discussing the design criteria more thoroughly with the engineering and art students, by generating assessment questions which reach higher on Bloom's Taxonomy, and by instituting a detailed assessment of the finalized designs. In addition, we have expanded our assessment to include the vehicle design teams. These new methods will aid us in proving or disproving our second hypothesis that increased comprehension of the converging-diverging framework leads to improved designs.

Appendix 1: Converging-Diverging Thought Learning Activity Questions

Score	Question # 1: If we think about the crane project in terms of a converging-diverging framework, what aspect of the project was *convergent design*?
5	Lists parameters of the project 100% of which were constrained OR shows that specific choices lead to better design solutions
4	Lists parameters of the project >=75% of which were constrained OR states the fact that choices were made which lead to better design solutions
3	Lists parameters of the project >50% of which were constrained OR states that choices were constrained
2	Lists parameters of the project >25% of which were constrained OR states that choices were made
1	Lists parameters of the project <=25% of which were constrained

Score	Question # 2: If we think about the crane project in terms of a converging-diverging framework, what aspect of the project was *convergent problem solving?*
5	Cites specific calculations or analyses and states they lead to improved design solutions
4	Cites specific calculations or analyses used to evaluate a design solution
3	Relates calculations and analyses to evaluation of design without citing specific types of calculations or analyses
2	States analysis and calculations where performed without relating to evaluation of design
1	Does not state calculations were performed that could lead to improved designs

Score	Question # 3: If we think about the crane project in terms of a converging-diverging framework, what aspect of the project was *divergent design?*
5	Lists parameters of the project 100% of which were unconstrained items OR shows that choices were made that broadened the ideas generated; fleshed out design space of this open-ended problem
4	List parameters of the project >=75% of which were unconstrained items OR discusses open-ended nature of the project in relation to specific project tasks
3	Lists parameters of the project >50% of which were unconstrained OR discusses open-ended nature of the project without relating it to specific unconstrained parameters or project tasks
2	Lists parameters of the project >25% of which were unconstrained OR discusses choices made which were unconstrained but does not mention open-ended nature of project tasks
1	Lists parameters of the project <=25% of which were unconstrained OR suggests that decisions lead to better design solutions directly

Score	Question # 4: Give an aspect of the Hoistinator or Bottle Rockets project which exemplifies each level of the learning pyramid.
Score is equal to the number of levels answered correctly.	

Appendix 2: Interface Design Heuristics

- **Visibility of system status**
  - The system should always keep users informed about what is going on, through appropriate feedback within reasonable time.
- **Match between system and the real world**
  - The system should speak the users' language, with words, phrases and concepts familiar to the user, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order.
- **User control and freedom**
  - Users often choose system functions by mistake and will need a clearly marked "emergency exit" to leave the unwanted state without having to go through an extended dialogue. Support undo and redo.
- **Consistency and standards**
  - Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform conventions.
- **Error prevention**
  - Even better than good error messages is a careful design which prevents a problem from occurring in the first place. Either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action.
- **Recognition rather than recall**
  - Minimize the user's memory load by making objects, actions, and options visible. The user should not have to remember information from one part of the dialogue to another. Instructions for use of the system should be visible or easily retrievable whenever appropriate.
- **Flexibility and efficiency of use**
  - Accelerators -- unseen by the novice user -- may often speed up the interaction for the expert user such that the system can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.
- **Aesthetic and minimalist design**
  - Dialogues should not contain information which is irrelevant or rarely needed. Every extra unit of information in a dialogue competes with the relevant units of information and diminishes their relative visibility.
- **Help users recognize, diagnose, and recover from errors**
  - Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution.
- **Help and documentation**
  - Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Any such information should be easy to search, focused on the user's task, list concrete steps to be carried out, and not be too large.

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