AC 2008-679: AN INVESTIGATION OF GAPS IN DESIGN PROCESS LEARNING: IS THERE A MISSING LINK BETWEEN BREADTH AND DEPTH?

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An Investigation of Gaps in Design Process Learning: Is there a Missing Link between Breadth and Depth?

Abstract

Teaching 'design' is an integral part of undergraduate engineering preparation. Most four year engineering programs include a first year course focused on the engineering design process where students are exposed to the wide range of issues that must be considered with regard to the 'real life' activity of designing a product or a process. These courses typically culminate in a team report describing the breadth of information accumulated and considered to arrive at the final recommended design. However, at the first year, students typically lack the knowledge to perform any meaningful analysis on their product or process, but rather focus their activities on the less 'technical' but equally important aspects of the design, such as consumer needs, economic impact, safety and design communication.

Once students leave their first year, the curriculum focus typically turns almost exclusively to teaching the analytical tools students will need as working engineers to accomplish innovative design, with far less emphasis on the broad design issues that extend beyond the analysis. Anecdotal evidence shows that students do not connect the newly acquired analytical knowledge with the design process, creating a design learning gap. When students return to a design emphasis in the senior year capstone course, they are expected to bridge this gap by synthesizing the broad engineering design understanding from the first year with their analytical depth gained in the second and third years to produce unique engineering design solutions. Can small but effective changes be made in the second and third year to improve this model of design learning that could help students more easily make the connection in the senior year between the broad design learning from three years earlier and their newly developed analytical skills? Through a joint effort involving faculty from Engineering Design, Engineering Mechanics, Civil Engineering, and Mechanical Engineering, we hope to answer just that question.

Critical evaluation to determine the effectiveness of any curricular innovation requires some type of concrete baseline evaluation prior to implementation of the innovation. An assessment of improvements to design learning is no different. Design learning and the related design ability have a three-pronged foundation: 1) design process knowledge, 2) creative processing ability, and 3) design analysis knowledge. During the fall 2007 semester, baseline data related to each of these components was collected from students across all four years and several engineering disciplines using the Comprehensive Assessment of Design Engineering Knowledge (CADEK) instrument, a divergent thinking measure, and a creative climate survey. In addition to serving as a benchmark for comparison after curricular innovations are implemented, this baseline data will also enable us to identify the hypothesized gaps in the ability to perform design at different stages of the four year program.

This paper reports on the preliminary findings of this initial data collection. The results of these measures will be used as a baseline in the spring semester to support curricular innovation through infusion of modular design activities and electronic portfolios in the second year strength of materials course, followed in fall 2008 by junior level ME and CE courses to improve design learning.

Overall, our preliminary analysis indicates that indeed design process learning is enhanced while divergent thinking and perceptions of creative climate diminishes over the course of the four years of undergraduate engineering education. Accordingly, based on our limited data set, we recommend curricular interventions in selected sophomore and junior courses that focus on creative design problem solving.

Introduction

In the past 20 years, much interest and effort has been directed toward increasing the design emphasis and adding related curriculum components in undergraduate engineering education. At most institutions in the US this effort has focused primarily on first year (cornerstone) and senior year (capstone) design courses. As stated by Dym[1], there is hard evidence that supports the "strong belief that first-year, cornerstone courses:

- enhance student interest in engineering;
- enhance student retention in engineering programs;
- motivate learning in upper division engineering science courses; and
- enhance performance in capstone design courses and experiences."

At this time, however, the emphasis in the second and third years has remained primarily on engineering science and analysis[1]. This begs the question, if adding design experience in the first and last years of traditional engineering curriculum has had such a positive effect, could the design knowledge, interest, and motivation of our students be further enhanced by incorporating design experiences into the second and third years as well? A few engineering programs have taken major steps to incorporate significant design experiences throughout all years of undergraduate study, but this seems to be the exception, not the rule. For example, at the Harvey Mudd College, design permeates the overall curriculum: "The *design and professional practice* stem includes five required courses that are designed to provide students with the means to work in teams on open-ended, externally-driven design projects that, over the course of the curriculum, encompass conceptual design, preliminary (or embodiment) design, and detailed design. 'Hands on' exposure to professional practice begins with students undertaking challenging design problems in the first year (E4), continues with a practicum (E8) on drawing and making objects, opportunities to develop and apply engineering judgment (E80), and culminates with three semesters of Engineering Clinic (E111-113).[2]"

Based on the format of most traditional engineering programs, however, it seems to be the prevailing opinion that the benefits gained through broad design study in the first year experience are enough to plant the seed that will grow quietly in the background while the curriculum focuses attention more intently on fostering analytical depth in the second and third years. Students in the senior year are then expected to harvest the fruit of the design knowledge that was planted in their first year and combine it with in-depth knowledge gained in the second and third years to complete significant design activities in the senior capstone design course, emerging as engineering graduates who are equally versed in design and analysis and able to combine these together to produce creative, innovative solutions.

I-Beam Design Learning Model

The traditional undergraduate engineering design learning model is illustrated in Figure 1. The wide top and bottom "flange" of the I shape represent the first year cornerstone and senior year capstone design experience, where design learning encompasses a broad range of subjects including customer needs assessment, concept generation and evaluation, design analysis, detailed design recommendations, and production. The narrow center "web" of the I shape represents second and third year course focus on analytical concepts and techniques ultimately intended to support comprehensive design analysis ability.

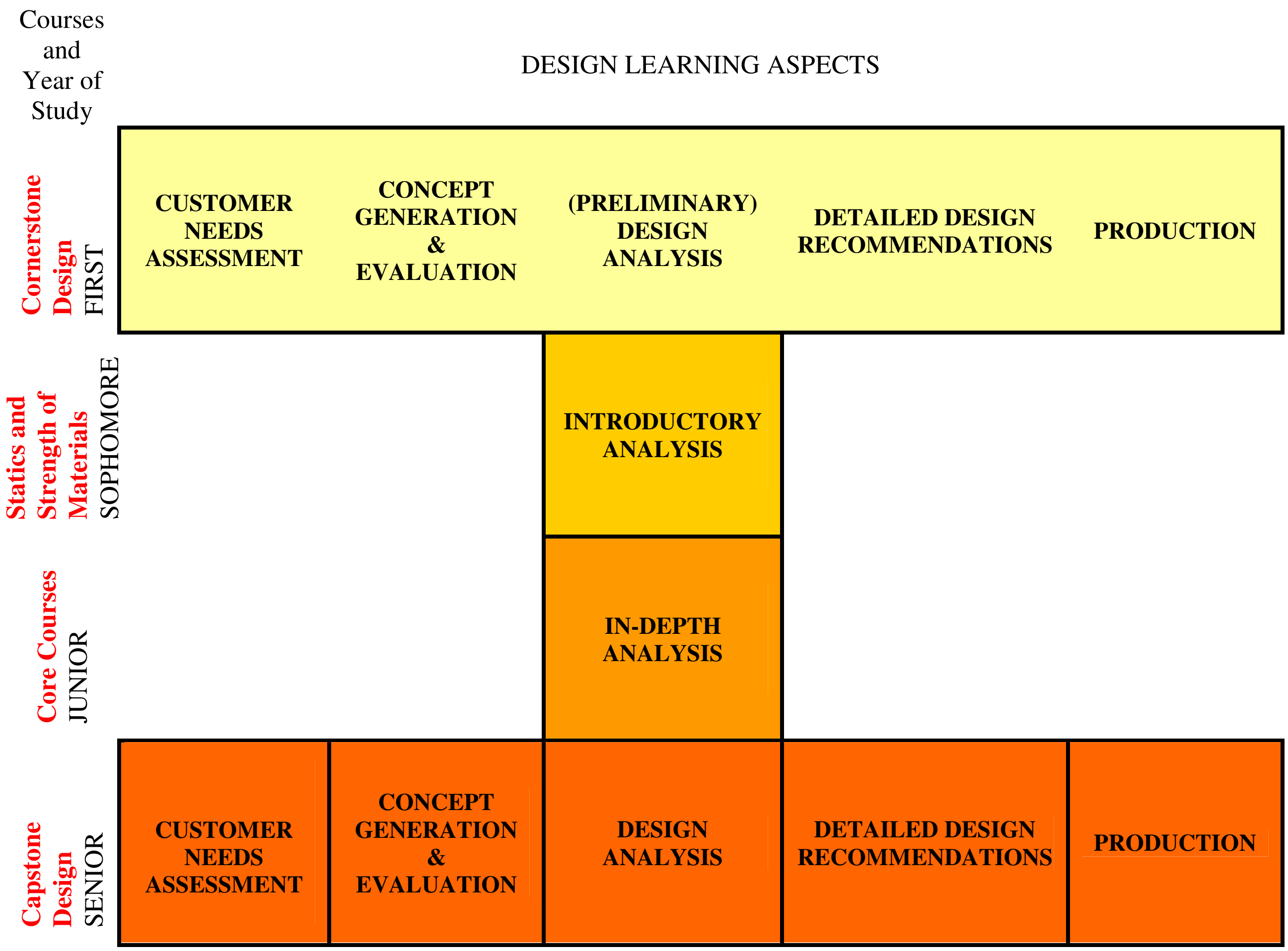

Figure 1: I-beam Model of Undergraduate Engineering Design Learning

Without any concrete design activities or discussions about the entire design process in the second and third year analysis courses, students might lose sight of the connection between the work they are doing in their analysis courses and concepts they learn in their cornerstone and capstone design courses. In terms of the I-beam analogy, the "weld" between the web and flange at both ends is weak, minimizing the structural integrity of the entire beam. Based on this model, a research effort funded by The Pennsylvania State University's Leonhard Center proposes that introducing design elements into the second and third year courses will strengthen the ties between design and analysis in the undergraduate engineering curriculum, improving the retention of design knowledge between the cornerstone and capstone experience, enhancing the interest and motivation of students in analysis courses, and making the educational experience more meaningful at all levels. The challenge is making the second and third year design activities detailed enough to produce meaningful results but simple enough that significant attention is not taken away from students' achievement of analytical goals and that the time required by students and faculty is not significantly increased.

Data Collection: Current Snapshot of Design Learning

Before proceeding with course changes aimed at achieving these objectives, it was necessary to identify a concrete means of objectively measuring the design process knowledge and ability of students both before and after implementing course changes. Accordingly, consultations with several experts who have backgrounds in engineering design and psychology established that design learning and the related design ability have a three-pronged foundation: 1) design process knowledge, 2) creative processing ability, and 3) design analysis knowledge.

The Comprehensive Assessment of Design Engineering Knowledge (CADEK) instrument [3] was administered to assess design process knowledge. The CADEK instrument was developed in spring 2005. Tests during the spring 2005 and fall 2006 semesters showed that the instrument successfully measured overall changes in design process knowledge and skills using 20 questions related to the engineering design process, working in teams, and design communication [4]. This instrument was also used to identify where in the curriculum students obtained their design process knowledge as it asks students to identify one or more courses in which they learned the content needed to answer each individual question.

To assess the divergent thinking of the students, a subscale of Torrance Test of Creative Thinking (TTCT) was used.[5] Specifically, the Unusual Uses Task was used which asks participants to generate as many unusual uses as they can for a tin can in a ten-minute period. The measure was scored for originality and fluency (i.e., number of ideas generated). The TTCT is the most widely used measure of divergent thinking ability.[6]

At the end of the fall 2007 semester, a slightly modified CADEK was administered and data collected from 367 Penn State engineering students. Two significant modifications were made to the original CADEK instrument for the purposes of this study. First, the questions were modified to allow students to identify any course as the source for their design learning, not just the first year cornerstone course. Second, due to the large number of students involved, several questions (particularly those measuring knowledge of design communication), were changed from open ended sketches to multiple choice to allow for electronic administration.

In an attempt to assess design process knowledge differences at all stages of undergraduate engineering education, rather than simply measuring the difference between the cornerstone and capstone experience, data was collected for second and third year students as well to gain a more complete picture of what is happening with student's design knowledge throughout the undergraduate engineering educational experience. In addition, we also wanted to measure differences in design learning across disciplines. To that end, third year data was collected from students in Civil Engineering (C E) and Mechanical Engineering (M E), the largest engineering programs at Penn State. In future semesters, these results will be compared to data collected from a broader range of engineering disciplines to determine not only design knowledge gains from course changes but also to identify similarities and differences in engineering design knowledge development across disciplines.

The CADEK answers were analyzed by a graduate student using a detailed evaluation rubric. For multiple-choice questions, 10 points were awarded for each correct answer and 0 points were awarded for each incorrect answer. However, the majority of the questions in the CADEK are open-ended, hence scoring them required a well-defined rubric. The evaluation rubric used for this study was developed from an analysis of typical student responses collected during the CADEK pilot testing. The evaluation rubric for question 1 from the CADEK is provided below in Figure 2.

A. In general, a process is an ordered set of activities to accomplish a goal. In the space below, describe your understanding of the engineering design process.

Engineering design process is a decision making process involving a series of iterative steps to develop a solution to problems either never solved before, or new solutions to problems that have been solved previously in a different way. We need to first identify the problem by firstly identifying the need. Once the need has been identified, the problem needs to be defined in clear and unambiguous terms. After identifying the problem, we need to then analyze what the problem demands. In other words, we need to gather pertinent information for the design, and research whether existing technologies can be incorporated into the design. A design engineer is expected to be creative when generating new ideas that may solve the problem. There can be several solutions to the given problem by considering different aspects. After generating the multiple solutions, we need to analyze each solution against the selection criteria for the problem in order to check whether it fits the requirements specified by the problem. After we have selected the best possible solution, we need to test that particular solution. Since the engineering design procedure is an iterative procedure, if there is a problem at this step we can go back and select the next best solution so the tests reveal positive results. Once the testing is complete, we need to document the solution to the problem clearly so that others can understand how the design engineer has solved the problem.

For complete points (at least 4 of the 7 steps, plus 1 or more alternative keywords)
1) Define problem 2) Customer needs assessment 3) Concept generation / brainstorm 4) Concept selection / best alternative/narrow 5) Preliminary design/ prototype / feasible design 6) Detailed/final design 7) Testing and/or implementation/document ***<u>Alternative Keywords:</u>*** iterative, design matrix, patent, Gantt chart, PERT, Pugh chart, PERT, benchmark, market research, timeline, evaluation criterion
For half points (less than 4 steps and/or following keywords)
define problem, narrow, improve/polish, choose, final design
Keywords for zero points
process, algorithm, step by step, solution, problem, design, achieve/accomplish goal

Figure 2: Evaluation Rubric Section from CADEK

To assess the students' perceptions of the creative environment, a creative climate measure was given. The measure was derived from the work of Hunter and colleagues.[7, 8] The 54-item measure is comprised of five factors: 1) work freedom and stimulation, 2) positive peer group and exchange, 3) instructor direction and influence, 4) organizational capacity and support (internal) and 5) organizational integration and extension (external). Factor scores represent averaged item scores within each factor and may range from 1 – 5. The average internal consistency estimates across the five factors was .86. Confirmatory factor analyses of the five factor model were supportive of the hypothesized structure: *GFI* = .946, *RMR* = .01, *RMSEA* = .067.

The baseline pilot data aimed to answer the following questions:

1) How is design process knowledge changing as students progress from their first to their last year as an undergraduate engineering student?
2) Is creativity and originality also changing during this time? And if so, how?
3) Are there significant differences between juniors and seniors in ME vs. CE in either design process knowledge or creativity and originality?

Participants

Data sets were collected from 367 engineering students; 19 first year students in EDSGN 100 (Introduction in Engineering Design), 256 second year students in E MCH 011 (Statics), 1 third year student in M E 340 (Mechanical Engineering Design Methodology), 87 third year students in C E 340 (Design of Concrete Structures), and 4 senior students in M E 440W (Senior Capstone Design Course).

The results and conclusions in this paper are based on a representative sample of all four years' pilot data. These students were chosen randomly via a random number generator (SPSS 16.2). This pilot sample is comprised of roughly twenty students for each year. As such, the results reported in this paper are preliminary and will be adjusted accordingly as more data is analyzed. The analysis results from the full data set will be included in the conference presentation.

Results and Conclusions

The pilot data that have been analyzed (*N* = 79) indicate a slight, albeit statistically insignificant increase in design knowledge across the four years (Figure 3). Freshman (*M* = 5.01, *SE* = .47), Sophomores (*M* = 5.36, *SE* = .30), Juniors (*M* = 5.96, .27), and Seniors (*M* = 5.97, *SE* = .53). The largest sample size was collected from the second year course. Although this data, when fully analyzed, may produce a statistically significant difference between the first and second year students, it will not be useful to determine differences between different engineering disciplines as students in their first and second year have not yet committed to a particular engineering major. Based on the third year student data, there does not appear to be a statistically significant difference between students from Civil Engineering (*M* = 5.89, *SE* =.23), and Mechanical Engineering (*M* = 5.95, *SE* = .45) students with regard to design knowledge.

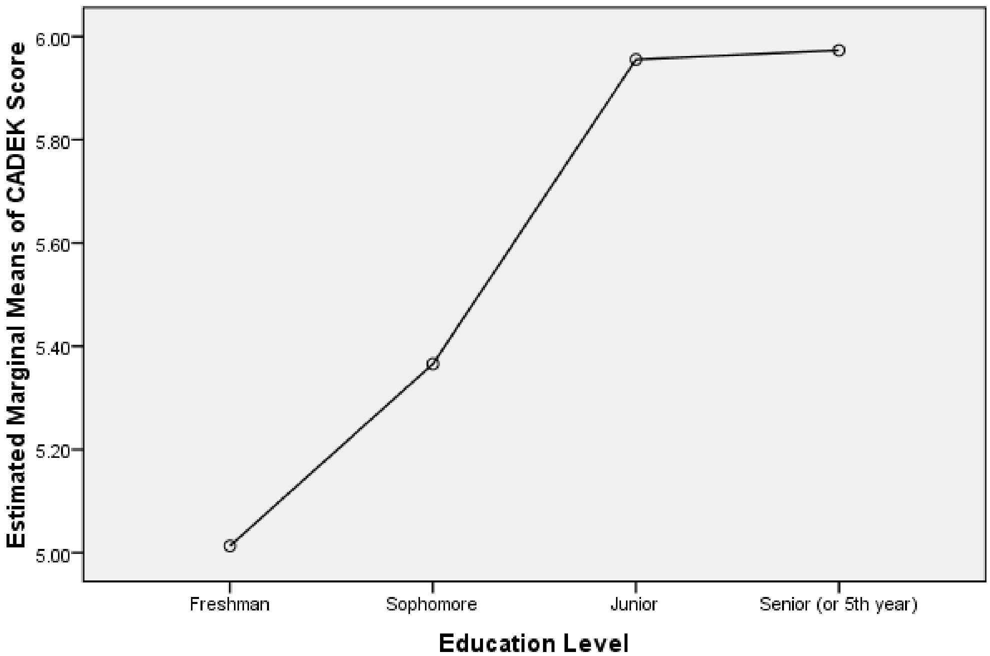

Figure 3. Mean CADEK Trend Across Four Academic Years

These results show that students in our sample are gaining in design process knowledge during their training at Penn State. Due to the statistical insignificance, we cannot generalize this conclusion. However, this insignificance could well be due to the small sample sizes in the various years. The question that arises is tied to the application of the design knowledge, which brings to the forefront the three-pronged nature of design learning (design process knowledge, design analysis, and creative processing). Are students motivated to apply their design process and analysis knowledge to create new, novel and innovative designs? To answer this question, students were also given a creative climate measure. The results of this measure indicate that although students appear to be gaining in design process knowledge, they do not perceive their environment to be more supportive of creative thinking as they move through their academic careers. In fact, results from an ANOVA analysis (F (3, 364) = 6.821; $p \leq .001$) suggest that students view their environment as *decreasingly* supportive of innovation over their four years at Penn State. Note Figure 4, for example, which depicts the significant decrease in perceived support from the college of engineering. In addition, results from the divergent thinking measure suggest that the originality and fluency of ideas generated decreases over the four years as well. Although statistically insignificant, these trends appear noteworthy (Figures 5 and 6). Thus, taken in conjunction these results suggest that an understanding of design learning involves not only the obtainment of design process knowledge but also the environment in which this knowledge may be applied. It appears critical that future studies explore this complex relationship further.

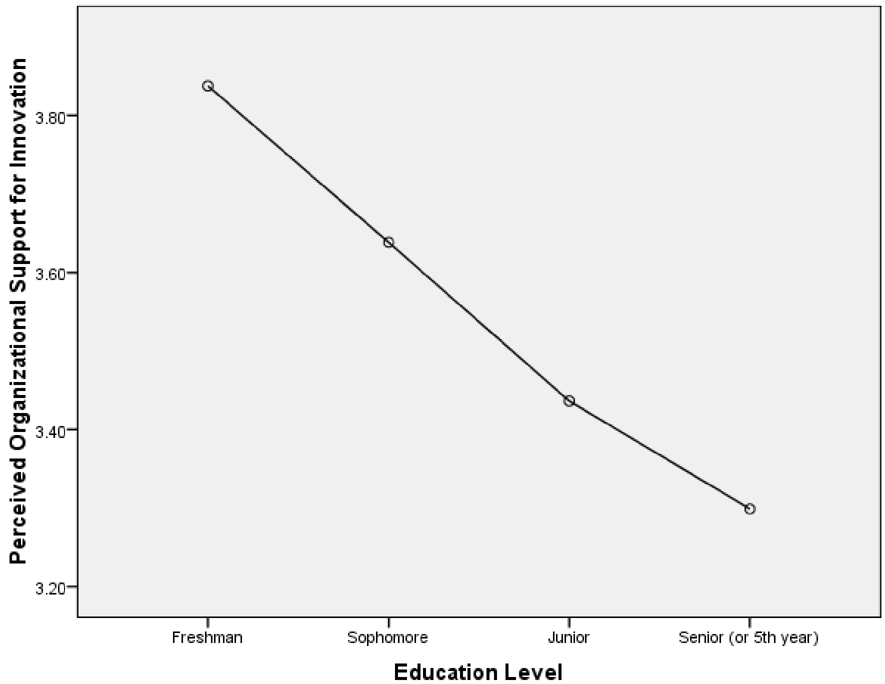

Figure 4. Mean Differences for “Perceived Organizational Support for Innovation”

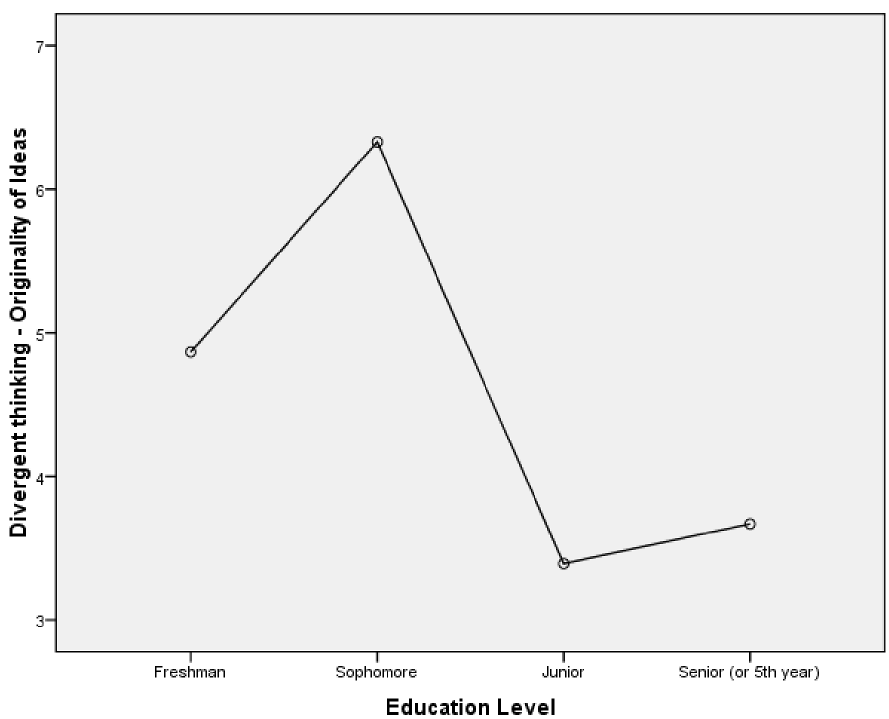

Figure 5. Mean Trends for the Number of Highly Original Ideas Generated in a Ten-minute Period

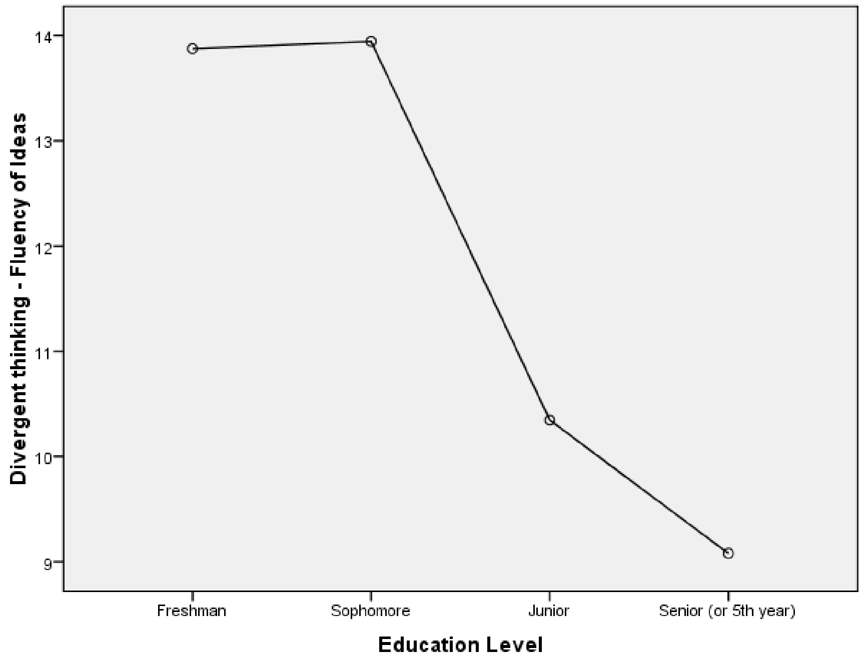

Figure 6. Mean Trends for the Fluency (i.e., number) of Ideas Generated in a Ten-minute Period

This situation of slightly increasing design knowledge but considerably decreasing originality and fluency of ideas generated in fact resonates with many. Industrial leaders long expressed a mounting concern about the impact of traditional engineering education on the creative potential of future engineers. A lack of creativity is viewed as problematic in a rapidly changing technology-oriented world where generating new ideas is essential to survival.[9] In addition, industry has perceived new BS engineering graduates as lacking design capability or creativity, as well as an appreciation for considering alternatives. Further, a 1995 ASME report ranked *creative thinking* as 5th of 56 top desired “best practices” for new BS-level engineers as seen by industry and academe.[10] In the past several years, universities have responded to these challenges by adding more design content and introducing more open-ended design problems into their engineering curricula. Articles discussing the guarded success of these initiatives have appeared in nearly every issue of the *Journal of Engineering Education* and the *International Journal of Engineering Education* over the last 10 years. Yet the need to increase the creative potential of graduates still persists.[11] In fact, our preliminary results confirm this.

Recognizing that other factors play a role as well, studies have documented (1) that people whose personality types indicate high levels of creative potential are leaving engineering at higher rates than the student body average and (2) faculty teaching methods lean heavily towards a ‘plug-and-chug’ approach to engineering problem solving, stifling creativity.[12] Indeed, one of the earliest accounts of this is by A.D. Moore [13] – an engineering professor - : “**I wish I could say that these educational areas [science and engineering] also have, as a main purpose, the stimulation of your creativity, and that they succeed in doing it. I am afraid that neither is true. In fact, I suspect that the taking of a degree in engineering or science may, in many cases, do more to stifle creativity than to stimulate it**.”

Looking at the bright side, design process knowledge of our students is increasing over time (though insignificant in this sample). As mentioned earlier, in addition to measuring design process knowledge, the CADEK also asks students to indicate in which course or courses the obtained the design process knowledge for each particular question. The table below summarizes the percentage of subjects in each cohort who listed a particular course or courses as the original of their design process knowledge. (Note: the percentages in this table do not add up to 100% because students were each allowed to specify more than one course for the origin of their design knowledge. Therefore these percentages represent the proportion of students in a particular cohort who attributed any portion of their design process learning to a particular course.) Not surprisingly, 90% percent of the students in the freshmen cohort said they have gained this knowledge from their first year cornerstone design course. (Note that students were allowed to indicate more than one choice of courses from which they have gained their design process knowledge). Despite the freshness of this course however, their (freshmen) design process knowledge is minimal in comparison to other cohorts. In a way, this shows that the "planted seed" is growing quietly in the background, and students get incremental design process knowledge from somewhat unexpected courses during their second year courses (Engineering Mechanics and Physics). Further, the cornerstone course was the most dominant choice by the junior and senior cohorts for acquiring the related knowledge.

	Freshman	**Sophomore**	**Junior**	**Senior**
Cornerstone Design Course	**90.0 %**	**80.0 %**	**89.5 %**	**72.2%**
Engineering Mechanics	**15.0 %**	**40.0 %**	**57.9 %**	**27.8 %**
Core Junior Level Course	**---**	**---**	**26.3 %**	**55.6 %**
Senior Capstone Design Course	**---**	**---**	**---**	**11.1 %**
Physics	**5.0 %**	**35.0 %**	**26.3 %**	**22.2 %**
Other	**10.0 %**	**15.0 %**	**26.3 %**	**16.7 %**

Table 1: Source of Design Process Learning as Identified by First Through Fourth Year Students

Future Plans

Due to the low number of participants during the fall 2007 study, CADEK, divergent thinking, and climate data will again be collected from a different set of first year students at the end of the spring 2008 semester. To expand the variety of disciplines considered in the study, the CADEK will also be giving to third year students in core courses of other majors as well. This data collection will expand the initial pre course implementation snapshot and increase the statistical power observed in the data.

In addition, second year students in six of the nine sections of E MCH 213 (Strength of Materials) will complete a mini-design project as a part of the traditional analysis coursework while the students in the remaining three sections will instead complete an extended writing assignment on career issues in several different engineering fields. This way, the workload for both sets will be comparable, but the experience will be different to help us determine if small-scale design activities can have a measurable influence on overall design knowledge. We will use the spring 2008 data collection to measure the effects of this implementation.

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