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Comparative Study of Undergraduate and Practicing Engineer Knowledge of the Roles of Problem Definition and Idea Generation in Design*

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Little doubt exists that globalization will be a dominant part of engineering in the twenty-first century. This major shift—from engineers collaborating and competing within a fairly limited region to engineers collaborating and competing around the world—will require engineers to possess different knowledge to be successful. Two areas of design knowledge that are becoming more important due to globalization are problem definition and idea generation. These areas of knowledge are cited as being important because they rely on 'right-brain' thinking in addition to analytical know-how, a combination that is more difficult to offshore. In this study, knowledge of the roles of problem definition and idea generation in engineering design is assessed over time: subjects are assessed before any college-level engineering, during their engineering education, and five or more years after starting to practice engineering. The primary assessment instrument involves subjects critiquing a proposed design process; their critiques are then analysed to determine what they know about the roles of problem definition and idea generation in design. Results show that no significant learning about problem definition occurs until an undergraduate's senior year, with large gains also made after graduation by practicing engineers. For idea generation, students learn a significant amount while enrolled in an introduction to engineering course, but lose this knowledge later during the curriculum.

Keywords: Engineering design; engineering education; global economy; problem definition; idea generation

MOTIVATION

THERE IS A GROWING CONSENSUS among those forecasting the environment in which US engineers of 2020 and beyond will be working—a consensus that globalization in general, and the emergence of India, China and other Asian countries as significant players in the world economy in particular, will drastically change the necessary skill set for US engineers if the United States is to remain economically strong. One can find this theme in prominent works such as Friedman's *The World is Flat* [1], Prestowitz's *Three Billion New Capitalists* [2] and in the National Academy of Engineer's *The Engineer of 2020* [3]. As globalization progresses, more and more of the traditional stronghold of engineers, 'left brain' analytical work, is being outsourced from the United States. And, as analytical work is outsourced, US engineers who want to be valuable to their employers (i.e. who want to have jobs) will need to have a different set of 'right brain' skills to complement their analytical foundation. As summarized by Felder [4], this different set of 'flat world' design skills includes:

- Creativity and ability to innovate;
- Ability to think systemically and across disciplinary boundaries;
- Interpersonal skills that allow engineers to better understand their customers' and commercial partners' needs;
- An ability for designers to integrate user-centred and aesthetic considerations with functional requirements;
- Language and cultural awareness skills;
- Ability to continually learn as technology changes.

For engineers to attain these skills, most assume that engineering education must change drastically from its current state. To better understand how much change in engineering education is necessary and the factors contributing to the development of these skills, it is important to understand the current knowledge of engineering students and practicing engineers with respect to these skills.

In this study, engineering students and engineers are assessed with respect to two areas of design knowledge for an engineer in a global economy. They are:

1) understanding the important role of problem definition in design;
2) understanding the important role of idea generation in design.

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Problem definition refers to activities aimed at the third bullet in the preceding list of 'flat world' skills from Felder, understanding stakeholder needs and defining requirements (e.g. focus groups, interviews, surveys, research on similar products, patent searches, etc.). Idea generation refers to activities related to creating solutions to the needs and requirements identified during problem definition (e.g. brainstorming, morphological charts, TRIZ). While generating a wide array of ideas is not the only path to creative solutions, idea generation is a key way that engineering educators help students learn how to reliably develop creative solutions. Both problem definition and idea generation are therefore linked to Felder's set of 'flat world' skills.

PURPOSE OF THIS STUDY

Comparing knowledge of the roles of problem definition and idea generation in design

Three different populations are in this study. Pre-engineering students were assessed during their first and last weeks in an introduction to engineering course. Engineering students were assessed at the beginning and end of their senior year. Finally, practicing engineers with at least five years of industrial experience were also assessed. With this sample, the following research questions (RQ) are addressed:

- RQ (1) Do students show differences in knowledge about the roles of problem definition or idea generation after a hands-on, team-based design class for first-year students (compared to before taking the class)?
- RQ (2) Do students at the end of a first-year design class show differences in knowledge about the roles of problem definition or idea generation compared to students beginning a senior capstone design class?
- RQ (3) Do students with industrial experience prior to starting senior year show differences in knowledge about the roles of problem definition or idea generation compared to students without prior industrial experience?
- RQ (4) Do students show differences in knowledge about the roles of problem definition or idea generation after a capstone design course (compared to before taking a capstone design course)?
    - RQ (4a) Does *prior industrial experience* affect the differences (or lack thereof) found in Research Question 4?
    - RQ (4b) Does a *multidisciplinary capstone project* affect the differences (or lack thereof) found in Research Question 4?
    - RQ (4c) Does *gender* affect the differences (or lack thereof) found in Research Question 4?
- RQ (5) How do practicing engineers with five or more years of experience differ from graduating seniors with respect to knowledge about the roles of problem definition or idea generation?

These questions aim not only to understand the baseline status for engineers at various points in their education and careers, but also to investigate the impact of first-year design courses, capstone design courses, and significant industrial experience on understanding the role of problem definition and idea generation in design.

PARTICIPANTS

Three sample populations were used in this research:

- Sample 1: n_1 = 286 first-year students at the University of Arizona were assessed both before and near the end of a hands-on, team-based introduction to engineering design class,
- Sample 2: n_2 = 103 seniors at the University of Arizona were assessed both before and near the end of their two-semester capstone design courses
- Sample 3: n_3 = 26 practicing engineers with five or more years of experience.

Sample 1: First-year students

The sample includes students who completed Engineering 102 at the University of Arizona in fall 2005. At the beginning of the semester, a total of 543 students were enrolled in ENGR 102. Although this course is geared toward first-year students, of the 543 students enrolled, 71 per cent were first-years, 21 per cent were sophomores, four per cent were juniors and four per cent were seniors. The course is structured such that each Monday is reserved for a fifty minute lecture with all enrolled students; then, the students split into sections for the remainder of the week. Each section is taught by a different professor. All subjects were assessed at the beginning and end of the course. Only the assessments from students who agreed to participate in the study and who completed both the pre- and post-tests were analyzed; with these deductions, the final sample size is 286 students.

Sample 2: Seniors

A group of 103 engineering students enrolled in the mechanical and multidisciplinary senior design courses during the 2005–6 academic year at the University of Arizona participated in the study. Participants self-selected by enrolling in either the mechanical or multidisciplinary design course. Materials science and optical engineering students were required to enroll in the multidisciplinary

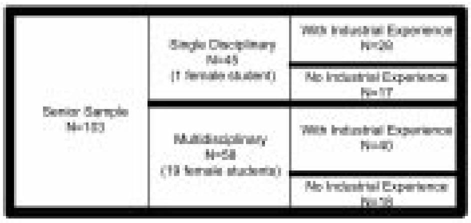


Fig. 1. Senior sample.

class, mechanical students could choose either one of the two courses, and other majors could select either a capstone class within their own discipline (not in this study) or the multidisciplinary course (in this study).

As shown in Fig. 1, forty-five participants were in the single disciplinary mechanical design course, of which twenty-eight had prior industrial experience and seventeen did not. Fifty-eight participants were in the multidisciplinary course, of which forty had prior industrial experience and eighteen did not. There was only one female student in the single disciplinary course while there were nineteen female students in the multidisciplinary course.

All subjects were assessed at the beginning and end of the course. Only the assessments from students who agreed to participate in the study and who completed both the pre- and post-tests were analyzed. Of 119 students completing pretests, 103 completed post-tests and are in this study: ten did not complete post-tests and six completed post-tests but elected not to be in the study.

Sample 3: Practicing engineers

Thirty-nine packets were sent to practicing engineers and 27 responded (69 per cent). Twenty-six of the respondents met the requirement of having five or more years of applied engineering experience. The participants were from 14 different companies: seven were from a major electronics manufacturer and no more than two participants were from any other single company. The participants averaged 20.1 years of total engineering experience (min = 5 years, max = 39 years) and 14.4 years of engineering design experience. Twenty of the respondents stated that their current position involved a significant amount of design. On average, the respondents indicated that 51 per cent of their current job activities involve design. Eighteen respondents hold at least one patent. Concerning education, five respondents earned a Ph.D., 13 earned master's degrees or higher and 25 earned a bachelor's degree. Of the bachelor's degrees, there are ten participants with mechanical engineering degrees, nine with electrical engineering, three with physics and one each with optical engineering, systems engineering and aerospace engineering.

Relevant aspects of the curriculum at the University of Arizona

Introduction to engineering design

Eleven sections of ENGR 102 participated in this study in fall 2005. For all eleven sections, the first 9.5 weeks of the semester had the same structure. During the first four weeks, teams were formed and students completed several assignments related to teamwork, design, and communication. The first project started in week 5 and ran for 5.5 weeks. This first project involved teams designing, building and testing a solar oven with a kit of materials. While this first project was analytically intensive, creativity and idea generation were also a focus. Problem definition was not a significant focus.

The second, team-based project ran roughly from week 10 to the end of the course (5.5 weeks) and varied between sections. Five sections worked on a project similar in structure to the solar oven, three on a product dissection project, and three worked with actual clients on service learning projects (each section's instructor selected which type of project to run in his/her section). Creativity was an element of all three of these types of projects. Problem definition was most strongly covered in the service learning projects: students met clients, defined their needs and expressed these needs as formal design requirements.

Despite the significant differences in projects in the different sections of ENGR 102, no significant difference in learning about engineering design was found—including no difference in learning about the role of problem definition or idea generation in design between the three types of projects [5].

Sophomore and Junior curricula

With respect to engineering design in general, and to understanding the role of problem definition and idea generation more specifically, the sophomore and junior curricula at the University of Arizona is similar to that at many other schools: there is essentially no emphasis on these topics. Instead, attention is turned to mastering the analytical basis for each engineering discipline during these two years. The one significant exception to this is the Department of Systems and Information Engineering, where problem definition is part of the discipline's core. There are not a significant number of systems engineering students in this study.

Capstone courses

Students in the mechanical and the multidisciplinary capstone courses are in this study. Both courses last two semesters and focus on a team-based engineering design project with a real client. These two courses were nearly identical in that all students attended the same classroom sessions and completed the same assignments. Perhaps the only relevant difference is that the multidisciplinary team reports were graded by the course instructors (ensuring that the teams used tools introduced in class correctly) while the single disciplinary team reports were graded by their team mentor (who in most cases was not intimately familiar with the design tools introduced in class).

Problem definition skills (including identifying needs, design requirements, functional requirements, the House of Quality and the overall process of working with a client to define requirements) were covered in detail and teams applied these skills to their capstone projects. Techniques for generating ideas were covered and students were expected to generate a wide array of concepts for their projects before selecting a smaller set to design and prototype.

APPARATUS

Subjects' critique of a proposed design process provided an approach to measure each student's design process knowledge [6]. The Gantt chart shown in Fig. 2 visually represents the critiqued process.

The students critique the process by identifying its pros and cons. A seven trait rubric created and evaluated by Bailey and Szabo [6] provided a scale for scoring the responses. Two of the seven traits of the rubric are relevant to the two design knowledge areas of interest in this paper: problem definition and idea generation.

Level 1. Problem definition

Explain why needs must be gathered and analys*e* the effectiveness of techniques for gathering needs.

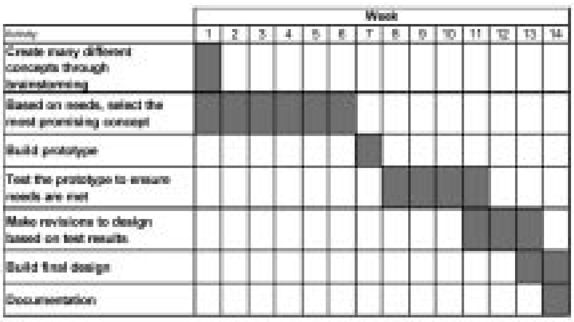


Fig. 2. Gantt chart of design process students critiqued.

Table 1. Example of ordinal scoring of rubric: trait 1

Points	Trait 1: Problem Definition/Needs Identification
0 points	No mention of problem definition/needs identification
1 point	States that gathering needs/requirements is important or should be included in the design process.
2 point	States that needs/requirements should be gathered *before brainstorming* in the proposed design process.
4 points	In addition to stating that needs/requirements should be gathered, gives a suggestion as to how to find needs/requirements

Level 2. Idea generation

Explain why multiple alternatives should be generated before developing a single alternative in depth.

For each of the seven traits, a set of ordinal scores is specified by the rubric. For instance, on Trait 1, the scores on the rubric are as shown in Table 1.

For Trait 2, which focuses on the role of idea generation, the rubric scoring scale is as shown in Table 2. The focus on Trait 2 is on students' recognition that spending time generating ideas is good. Because brainstorming is the most often-cited idea generation tool by students, it is explicitly referred to in the rubric. Referring to brainstorming is not necessary to receive two points on Trait 2, nor is it the only tool that can be focused on to receive two points.

In addition to the design process critique, seniors in the capstone course were asked about any prior industrial experience. The practicing engineers were also asked a variety of background questions about their industrial experience and educational background.

One final instrument, based on an instrument used by Mosborg, *et al.*, [7] and Newstetter and McCracken [8], was used with the practicing engineers. The students were asked to mark the six most important design activities and the six least important from a list of twenty-three activities. While this instrument was primarily included to compare the sample to that in Mosborg's study (to evaluate if our sample of practicing engineers is a representative sample), it also provides a mechanism to compare what the subjects say

Table 2. Example of ordinal scoring of rubric: trait 2

Points	Trait 2: Idea Generation
0 points	No mention of idea generation/brainstorming.
2 points	States that it is good that multiple concepts are created or that brainstorming is good/needs more time.

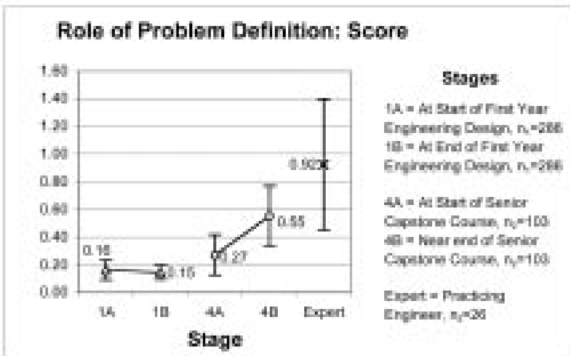
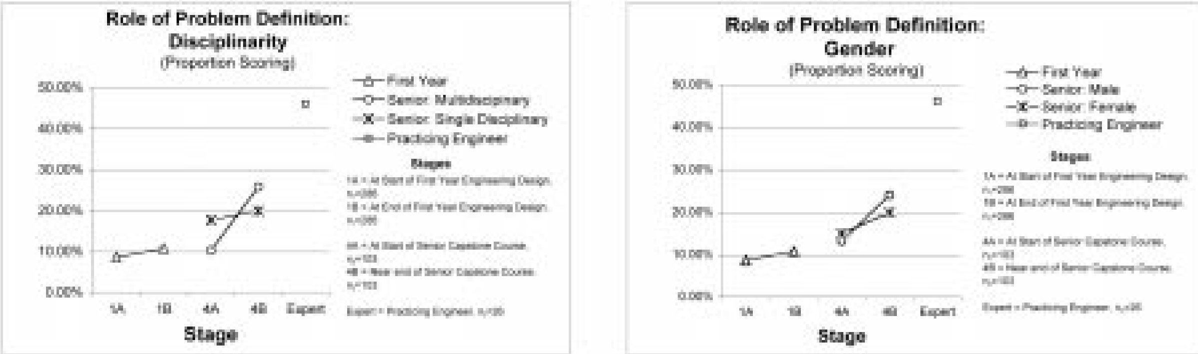


Fig. 3. Problem definition (Trait 1) scores 95% confidence intervals.



(a) Multi *vs.* Single Disciplinary (b) Gender

Fig. 4. Problem definition (trait 1): % scoring on Trait 1; interactions are not significant at $\alpha = 0.05$.

they think is important and what they actually identify in the design process critique as important.

RESULTS

Role of problem definition

The average scores for each sample on the design process critique Trait 1, which deals with understanding the role of problem definition in design, is shown in Fig. 3.

The difference between scores before a capstone course and after it is statistically significant, Wilcoxon $Z_{obt} = -2.188$, $p = 0.029$. The difference between graduating seniors and practicing engineers is also statistically significant, Mann-Whitney $Z_{obt} = -2.035$, $p = 0.042$.

When the effects of prior experience, being in a multidisciplinary course and gender on learning in a capstone course are investigated, no statistically significant interactions are discovered. This was determined using a test of proportions*. While the plots (Fig. 4) show that being in a multidisciplinary class and being male increase the amount learned during capstone about the role of problem definition, neither of these interactions is significant at an alpha level of 0.05.

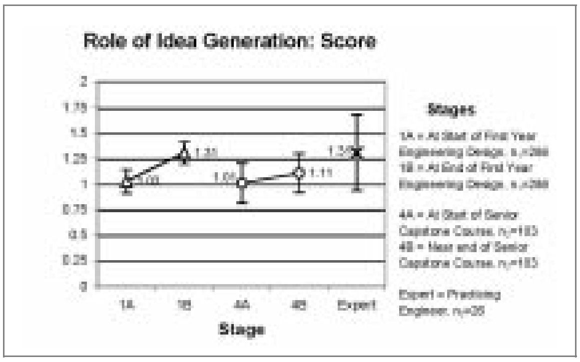


Fig. 5. Idea generation (Trait 2) scores 95% confidence intervals.

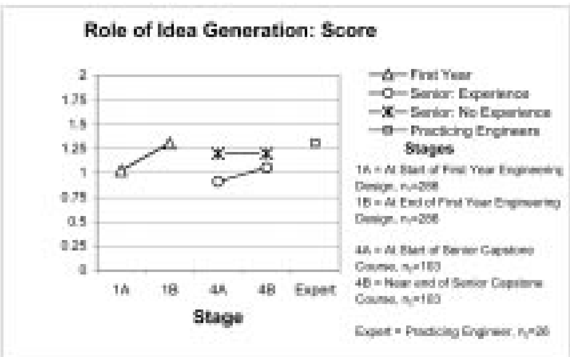


Fig. 6. Idea generation (Trait 2): % scoring on trait 2.

Role of idea generation

The average scores for each sample on the design process critique Trait 2, which deals with understanding the role of idea generation in design, is shown in Fig. 5.

On Trait 2, respondents either earned 0 points or 2 points. Because Trait 2 is binary (i.e. you either score two points or you earn no points), a test of proportions is used to compare samples. Using a test of proportions and an alpha level of 0.05, the effect of the introduction to engineering course on first-year students is statistically significant [$Z_{obt} = 3.428$, Z_{crit} ($\alpha = 0.05$) = 1.96]. In addition, the decrease in knowledge between the first year and senior year is statistically significant at an alpha level of 0.05 [$Z_{obt} = -2.626$, Z_{crit} ($\alpha = 0.05$) = 1.96]—this drop in knowledge is most significant in students with industrial experience, as shown in Fig. 6 [$Z_{obt} = -2.97$, Z_{crit} ($\alpha = 0.05$) = 1.96]. The improvement in score between graduating seniors and practicing engineers is not statistically significant at an alpha level of 0.05.

When the effects of prior experience, being in a multidisciplinary course, and gender on learning in

* A statistical tool for evaluating interactions between ordinal scores is not available. Hence, a test of proportions (a non-parametric test) is performed for each trait. For the test of proportions, responses are coded as a binary variable (as either receiving points for a certain trait or not); *how many* points are earned on a certain trait cannot be analysed with this test.

a capstone course are investigated, no statistically significant interactions are discovered. Figure 6 does show that seniors with prior industrial experience do reduce the difference between them and their peers without prior industrial experience during the capstone course, but this interaction is not statistically significant.

Design activity checklist

Of the twenty-three activities that practicing engineers rated as either one of the six most important activities in design or one of the six least important, four are related to needs identification/problem definition and four are related to idea generation. The results, expressed as the percent of respondents that marked each activity as one of the most important and percent that marked each activity as one of the least important, are shown in Table 3 and 4.

Based on these data, practicing engineers show clear support for need identification/problem definition as an important activity in design. The results for idea generation are more mixed, with 'brainstorming' receiving significant support and 'using creativity' and 'generating alternatives' not getting much support. Because these three activities are very similar, it is likely that a respondent would only mark one of them in their list of six most important activities—and people would see 'brainstorming' first as it is the second activity on the list (the activities were not put in a random order so that this study could replicate the Mosborg, *et al.*, study [7] where the order was static).

DISCUSSION

The discussion addresses each of the five research questions.

Research question 1: differences before and after a first-year engineering design course

Based on the design process critique, no differences in student knowledge of the role of problem definition were found before and after the first-year, hands-on, team-based design course. Significant differences were found during this time period, however, in students' understanding that idea generation is an important part of design.

Both of these topics, problem definition and idea generation, were covered in the first-year course. Therefore, the lack of learning about problem definition is not for a lack of exposure to or experience with problem definition in the context of engineering design. Several alternative hypotheses exist, including that first-year students are not intellectually mature enough to be able to explain the role of problem definition in design, that the course was poorly taught, that the exposure to the material was ineffective, or that factors not included in this study (e.g. other courses) had significant effects on student design learning.

Research questions 2 and 3: differences between students at the end of their first year and students at the start of their senior year, including impacts of industrial experience

No change is seen between first year and senior year with respect to understanding the role of problem definition. Concerning idea generation, however, students with industrial experience before their capstone show a statistically significant decrease in knowledge during this time period (those without industrial experience do not show a significant change).

When this decrease was first observed by Bailey in [9], one hypothesis was that it was because idea generation is not valued or practiced in industry [10]. Evidence here counters that hypothesis: not only do practicing engineers score well on Trait 2 of

Table 3. Activities related to problem definition (practicing engineers sample)

	Our Sample (n = 25)		Mosborg *et al.* Sample [7]	
Activity	% Marking as *Most* Important	% Marking as *Least* Important	% Marking as *Most* Important	% Marking as *Least* Important
Identifying constraints	60%	0%	68%	5%
Understanding the problem	76%	0%	80%	0%
Goal setting	20%	20%	10%	26%
Seeking Information	24%	4%	32%	10%

Table 4. Activities related to idea generation problem definition (practicing engineers sample)

	Our Sample (n = 25)		Mosborg *et al.* Sample [7]	
Activity	% Marking as *Most* Important	% Marking as *Least* Important	% Marking as *Most* Important	% Marking as *Least* Important
Brainstorming	52%	4%	42%	5%
Generating alternatives	12%	16%	31%	10%
Synthesizing	8%	72%	15%	52%
Using creativity	0%	16%	16%	16%

the design process critique, they also show at least moderate support for idea generation and related activities through the design activity checklist.

The other hypothesis asserted by Bailey [9], referred to as the 'snapshot' hypothesis, is that idea generation may be practiced in industry but not by interns and co-ops. Interns get a 'snapshot' of design during a summer job, where, for instance, they may be conducting tests on a design, making drawings, writing code, or analysing a specific part. 'This focus on small aspects of design and the lack of experiencing a full design project from start to finish compose the "snapshot" nature of most undergraduate internships' [9]. The snapshot hypothesis remains a likely reason why knowledge about the role of idea generation in design decreases for those students with industrial experience.

Research question 4: differences before and after a senior capstone design course

Improvement in knowledge about the role of problem definition in design is finally seen after the capstone course. This supports the hypothesis that learning about the role of problem definition in design requires more maturity than the population of first-year students possesses. It does not, however, rule out the possibility of other hypotheses (such as the quality of teaching or the effectiveness of the design experiences) explaining student learning about problem definition.

Differences in student knowledge about the role of idea generation before and after the capstone experience are not statistically significant, but those students with prior industrial experience do slightly close the gap between themselves and their peers without prior industrial experience (this closing of the gap, however, is not statistically significant).

No statistically significant differences in knowledge change before and after capstone were found between multidisciplinary vs. single disciplinary projects, prior industrial experience vs. no prior industrial experience, or female vs. male. The closest to statistically significant are the gains students on multidisciplinary projects made on problem definition knowledge that are greater than the change in knowledge for students on single disciplinary projects.

Research question 5: differences between graduating seniors and practicing engineers

Based on the design process critique, practicing engineers show a significantly higher understanding of the role of problem definition in design compared to graduating seniors. This provides further support for the hypothesis that this is a knowledge area that requires a high level of intellectual maturity. Another possible source of high scores for practicing engineers is their experience with projects where poor problem definition caused serious problems. Further work is needed to understand which, if either, of these two hypotheses explains why practicing engineers know significantly more than graduating seniors about the role of problem definition in design.

With respect to understanding the role of idea generation, practicing engineers score very similarly to first-year students at the end of the introduction to engineering design course (based on the design process critique). Because both groups score similarly and no group scores higher than these two, a possible conclusion is that they are both hitting a ceiling in terms of knowledge about idea generation's role.

CLOSURE AND BROADER IMPLICATIONS OF RESULTS

Returning to the motivating topic for these comparisons, globalization, the key question is: how can engineering curricula be changed to better equip graduates with flat world design skills?

With respect to understanding the role of problem definition in design, we show that addressing this topic for one term with first-year students and then not addressing it again until the senior year is not effective. The data suggest that significant learning about the role of problem definition does not occur until the capstone course. Continual work each semester from the first term forward, however, could prove to be effective (such a curriculum is not studied here).

There is weak evidence that multidisciplinary capstone projects improve knowledge about the role of problem definition more than single disciplinary capstone projects. Further exploration of this topic is warranted.

With respect to understanding the role of idea generation in design, first-year design students can make great gains in knowledge—leading to knowledge that matches the knowledge of practicing engineers. Unfortunately, this knowledge regresses to pre-first-year levels by the time students start their senior capstone experience—this regression is particularly true for students obtaining industrial experience. The capstone course is not enough to reverse this decrease in knowledge. A successful change for a curriculum with respect to idea generation would find a way to maintain the knowledge gained during the first semester straight through to graduation. A curriculum in which design was integrated throughout each term would be a strong candidate to accomplish this goal.

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