A MODULE TO FOSTER ENGINEERING CREATIVITY:

an Interpolative Design Problem and an Extrapolative Research Project

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Teaching techniques that enhance creativity are as critical as teaching technical skills. Innovation, the result of the creative process, is necessary for technological advancement and is highly correlated with economic prosperity and success.[1, 2] While creativity and innovation play a role in most aspects of engineering, they are rarely discussed explicitly in engineering courses. Engineers typically receive instruction in scientific principles and their conceptual application, but seldom do they receive formal instruction in creative problem solving.[3-5] It is particularly important to focus on creativity in introductory engineering courses to retain independent thinkers who tend to leave university earlier than others.[6] In addition, tools that enhance creativity are necessary because of increased employment in the life sciences and a general expansion in career opportunities for chemical engineers.[7-12] Creativity skills enable engineers to learn new material faster and improve interactions with colleagues in other disciplines.

Throughout my teaching experience I have been asked by many students how they can improve their creativity and problem-solving skills. From these experiences, I have noticed that many students limit their creative potential by censoring their ideas before fully investigating them. Encouraging students to pursue ideas regardless of how outlandish the ideas appear produces more vibrant, diverse, and ultimately useful output. Formalization of this instruction process will benefit a greater population of students than individual interactions alone.

Engineering creativity can be broken down into two distinct steps: idea generation and idea analysis. Success with creativity dependents on the number of ideas formed and the ability to perform these two steps be separately.[4, 13-15] Generating a large number of ideas, regardless of their quality, increases the likelihood that an innovative concept will be discovered.[13-16] Students who struggle with open-ended problems often try to combine idea analysis and generation. Analysis requires contradictory thought processes that can poison self-confidence and tolerance of risk, which are necessary for idea generation. During the brainstorming step, overly critical analysis limits the formation of the random and disparate connections that are needed to generate long lists of potential ideas, which often leads to abandonment of the most tangential and innovative ideas.

Here I describe a teaching module that can be integrated into an introductory chemical engineering course to maximize students' creative potential. This module builds upon previous efforts that have shown that creativity can be taught in the classroom.[1, 15, 17] This module includes an exercise to illustrate engineering creativity, an open-ended research project, and a questionnaire to assess individual creativity. The material that describes the role of creativity in engineering can typically be described in one or two lectures.

IDEA GENERATION

Idea generation is a highly personal process that varies greatly from person to person. Many techniques have been described to explain the workings of this process,[4, 13, 15, 18] including brainstorming,[19, 20] synectics,[21, 22] and lateral thinking.[23, 24] Creativity in engineering is dependent on many

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factors, including innate ability, experience, and good mental habits.[15, 16] While some students have more innate ability and experience from which to draw, many students fall into mental traps that limit their creative potential. Reading and exposure to experiences outside of engineering often enhances creativity.[25] A creative environment encourages independent thinking, self-awareness, openness to experience, and breadth of vision.[6, 18]

When struggling to generate novel ideas, students should be encouraged to use their own personal experiences. The most creative ideas often come from students who can effectively use their personal experiences and knowledge base. For example, a foreign student in a bioprocess engineering course I taught in 2003 had worked previously in a laboratory studying gene therapy. She was from a tropical country and had a family that had been painfully affected by malaria. Putting these two experiences together, she came up with an idea to manipulate the sickle cell gene to provide protection against malaria. Similar ideas could not be found in the literature, and this approach has therapeutic promise. This example illustrates how connecting personal experience (malaria) with educational knowledge (gene therapy) can lead to innovation.

EXTRAPOLATIVE VS. INTERPOLATIVE PROBLEMS

To help students with open-ended tasks I suggest that creative problems be divided into two distinct modes: extrapolative and interpolative. These two modes are defined by how the goals of the problem relate to known facts. Interpolative creativity is the creation of connections between known facts to arrive at clearly defined goals. Extrapolative creativity is the creation of new ideas as an outgrowth from known facts toward more loosely defined goals. For example, mass and energy balance problems require interpolative creativity; research papers predominately require extrapolative creativity; and process design requires elements of both. Typically, engineering students prefer interpolative problems. Both types of problems, however, require the generation of many high-quality ideas and the confidence to generate them. Understanding the similarity of the tools needed to address these two modes will enhance students' ability with open-ended problems.

Classic examples of problems that require interpolative creativity are the mass balance problems encountered in introductory chemical engineering courses (Figure 1). Problems of this type require small creative steps when drawing system boundaries. For the example in Figure 1, three different choices are possible: around unit A, around unit B, and an overall balance. More complex problems would have more possibilities, with some being difficult to identify on first observation. Many students start such a problem by writing mass balance equations around unit A before conceptualizing all possible system boundaries. In doing so, they miss that an overall balance is necessary to solve the problem. Generating a list of possible boundaries (ideas) before analyzing them would help students solve these problems more efficiently.

A research paper is good example of an extrapolative creativity problem that students often encounter. When assigned extrapolative problems, students should use similar techniques to generate ideas as they do with interpolative problems. Idea generation is complicated for open-ended problems by the "fear of a blank page" that leaves students not knowing where to start. As with interpolative problems, practice generating disparate ideas before evaluating them can help with the extrapolative creative process. Different from interpolative problems, loosely defined goals can make the brainstorming space seem limitless. To overcome this apparent limitlessness, students should be encouraged to use their previous experience and prior knowledge to redefine the goals of the assignment. They should especially be encouraged to use those experiences outside of engineering. For example, a student struggling to find a subject for a research paper (as described in detail below) found a clever topic by exploring his hobbies. This student was an avid bicyclist who had recently paid too much for a high-end bicycle. He chose to write a paper about ways to improve the production of titanium and reduce its cost, which turned out to be a well-defined and interesting project that the student found highly rewarding.

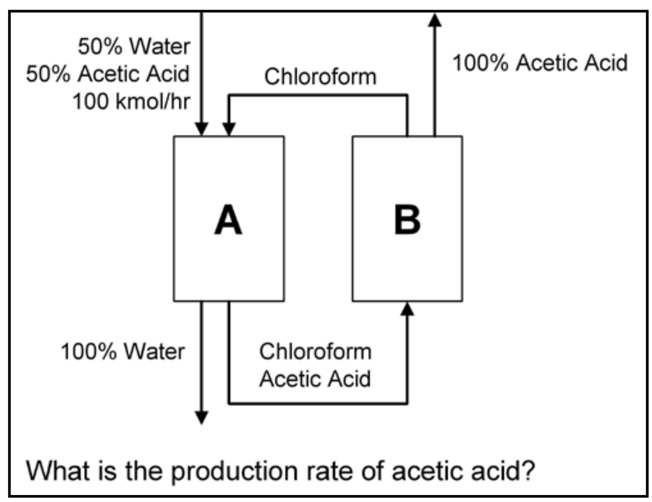

Figure 1. *Simple mass balance problem to illustrate interpolative creativity. An equimolar stream of water and acetic acid is fed to a liquid-liquid exchanger (A), which partitions the acetic acid into a chloroform extract and produces an idealized pure water stream. The acetic acid is removed from the chloroform by distillation (B). Three different system boundaries can be drawn: around A, around B, and around the entire process. Without knowing the recycle rate of chloroform an entire process balance is necessary to calculate the production rate of acetic acid. Identifying many possible solutions (in this case system boundaries) is necessary to solve interpolative problems.*

EXERCISE TO DEMONSTRATE ENGINEERING CREATIVITY

The following interpolative exercise is a project to design column packing material that illustrates engineering creativity. Presenting this exercise during class complements the lectures and provides a defined time period for students to practice their creativity skills. The exercise is comprised of two parts that are to be administered before and after instruction on creativity. Designing column packing is a geometric problem that has many possible solutions, is complex enough that an optimal solution cannot be ascertained on first inspection, but is simple enough to allow students to easily analyze their ideas. This exercise complements the extrapolative brainstorming problems[5, 13] and interpolative, brain teasers[15, 17] that have been described previously. The complexity of this problem illustrates to students how separating brainstorming and analysis can produce many distinct and effective designs.

There are currently numerous designs and shapes of column packing commercially available (Figure 2). Most of these designs were determined by a combination of experimentation, trial and error, and experience.[26] While the shape of the packing materials significantly affects their behavior, the optimal shape cannot be determined theoretically. The best packing materials have a high surface area for mass transfer and a low resistance to gas flow.[26, 27]

To begin the exercise the entire column packing simulation is described in detail. The overall goal of the process is to design a packing material that maximizes productivity in a packed column absorber. To make the design of packing material a tractable creativity exercise it was reduced to two dimensions. During the exercise, packing materials are designed on

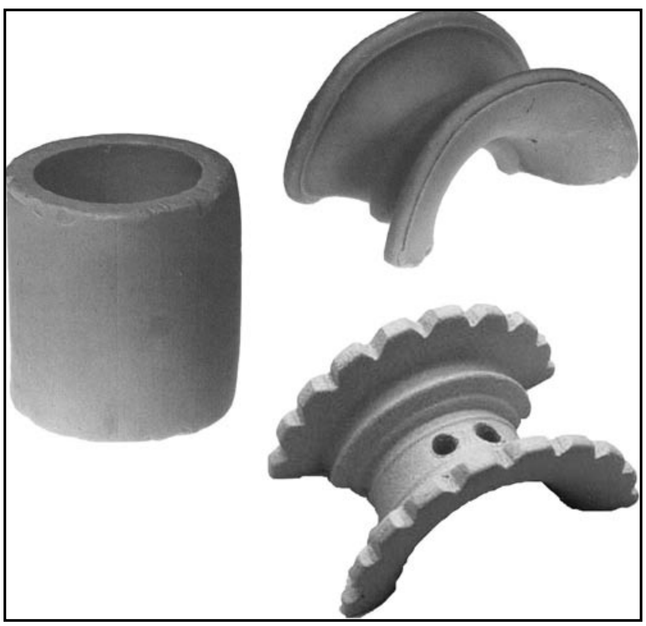

Figure 2. *Examples of commercially available column packing materials.*

11×11 grids and are filled into a theoretical 59×51 column using a stochastic Visual Basic simulator (Figure 3, which is available upon request). Packing designs must be physically possible, single pieces: all pixels in each design must share a border with at least one other pixel (as in Figures 2-4). The simulator fills the column by rotating the two-dimensional designs and placing them as close to the bottom of the column as possible without overlapping already packed pieces (Figure 3). Once the simulator has filled the column, it calculates the overall void fraction from the percentage of empty space and the surface area from the length of exposed edges. For simplicity, the gas flowrate and the overall production rate are assumed to be directly proportional to the void fraction. The simulator determines the performance of packing materials by multiplying the void fraction by the surface area.

As an example of packing material simulation, a solid square (Figure 3A) has a void fraction of 0.359, a surface area of 616, and a productivity of 221. It is a poor performer because it does not have much surface area. A better design would be a crossed I-bar (Figure 3B), which has a void fraction of 0.726, a surface area of 1,641, and a productivity of 1,192. These two examples demonstrate why this problem is useful for demonstrating the utility of engineering creativity. While void fraction and surface area are coupled to each other, good designs can independently increase both independently. In addition, the nonlinear relationship between these two parameters makes theoretical prediction of an optimum design difficult.

The exercise is broken into two parts. In the first part, prior to instruction on creativity, students are provided with the

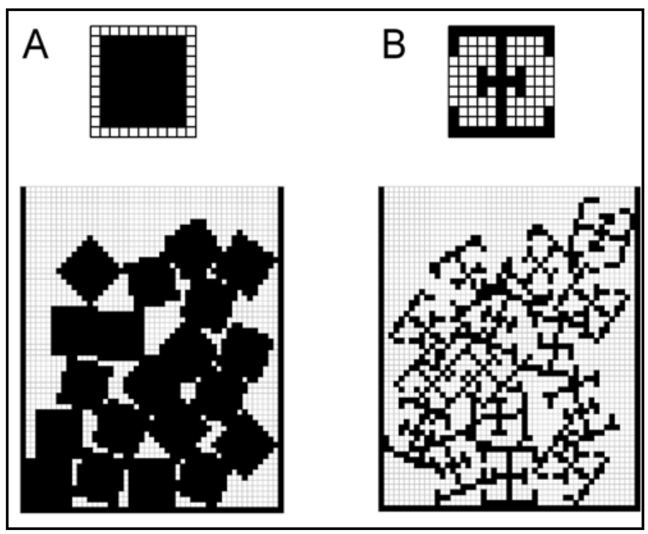

Figure 3. *Two examples of packing materials filling a two-dimensional column. The solid square packing (A) is a poor performer. When packed it had a void fraction of 0.359, a surface area of 616 and an overall productivity of 221. The I-bar packing (B) is a much better performer. When packed it had a void fraction of 0.726, a surface area of 1,641 and an overall productivity of 1,192. All values are dimensionless.*

packing simulator, and asked to create designs with the greatest productivity that they can in 10 minutes. During this time, students generate only a few designs with little variation. At the end of this period, students are introduced, by lecture, to the creativity techniques describe above, with emphasis on the utility of generating many disparate ideas and decoupling idea generation and analysis.

In the second part of the exercise students are provided with a handout containing a set of 11 × 11 grids on which to design packing materials by hand (Figure 4). Students are asked to generate as many packing designs as possible without analysis in 10 minutes. Their ideas for packing designs can be entirely disparate or can build upon each other. If the ideas build upon each other, students could provide an explanation of how it improves on previous ideas (Figure 4). Students are encouraged, however, to have as many disparate design ideas as possible, so as to add new possibilities regardless of whether productivity is improved. Creating only ideas that obviously improve productivity could potentially limit the creative process. After the 10-minute idea generation period, students return to the simulator and determine the void fraction, surface area, and productivity of each design. This second part of the exercise is intended to illustrate the benefit of generating a large number of potential designs before analysis. Students will find that while many designs perform poorly, some outlandish ideas will outperform their best ideas from the first part of the exercise. Typically, classes observe that students who have generated the most ideas also have the most productive designs.

CREATIVITY IN AN ENGINEERING RESEARCH PROJECT

Open-ended literature research projects are an excellent mechanism to illustrate extrapolative engineering creativity to introductory engineering students. This section describes a short research project in which students are asked to describe an aspect of chemical engineering that has a significant impact on society. Students can approach this broad assignment from two directions; they can either 1) describe a novel technology that could be used for societal benefit using engineering principles, or 2) describe a societal problem that could be addressed by novel chemical engineering methods. In other words, focus can be on either the technology or the societal problem. Students are encouraged to identify topics that are interesting and personally significant to them. Identifying novel and appropriate topics can be a daunting task for some student and requires considerable effort and creativity. The techniques described to enhance creativity can be especially helpful during the initial topic-identification period of this assignment.

The final paper should 1) fully describe the technology or societal problem, 2) describe how the technology addresses a problem or how the problem could be addressed with technology, 3) describe challenges that exist in the application of the technology or the solution of the problem, and 4) cite at least three references supporting all technical claims. Because the focus of the assignment is on the generation of a novel idea, the paper can be short, about 3-5 pages. In addition, an important component of the assignment is exploration of the scientific literature. In the process of exploration students will learn how large or small their chosen fields are and how difficult it can be to generate truly novel ideas.

When first introduced, students are not given any specific guidance to help generate ideas. Many students have difficulty with this aspect of the assignment. Generating new technical ideas is a skill that students are not typically exposed to in high school education. After allowing students a few days to independently struggle with creative idea generation, the lectures and exercises described in the sections above are presented. Students are then asked to return to the task of idea generation. They are encouraged to use the literature and their personal experiences to generate as many topics as possible before evaluating them. Once a reasonable list is generated, students use the literature, peer review, and their own judgment to pick the best one. Students are told to rate their ideas based on 1) novelty, 2) scientific correctness, 3) interest, 4) potential societal benefit, 5) feasibility, and 6) testability. A good idea will also not be too large (*i.e.*, catalysis or energy) that it cannot be easily summarized or be too small that not

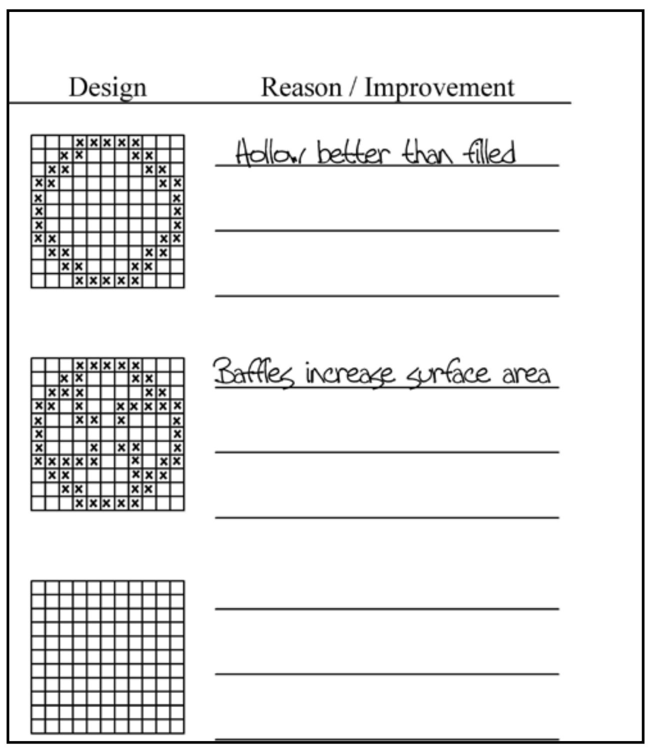

Figure 4. *Portion of student handout used to design two-dimensional column packing material containing two designs and brief rationales justifying them.*

enough information is available. Most students find that the challenge of generating ideas for this assignment, similar to the in-class exercise, helps foster their engineering creativity and improves the quality of their ideas.

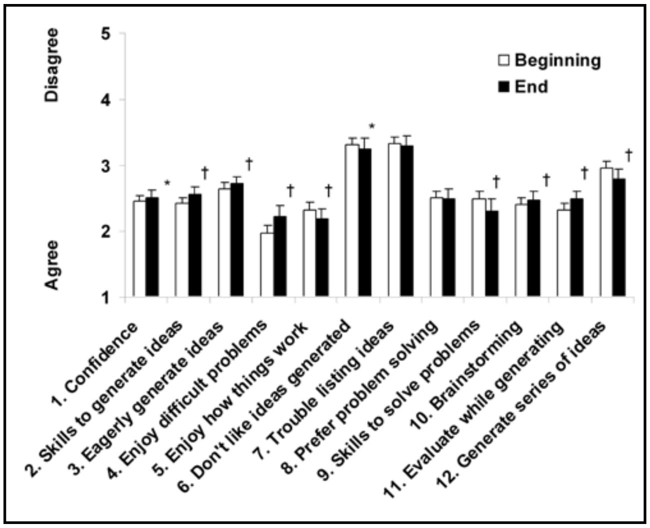

***Figure 5.** Results of creativity survey administered to first-year chemical engineering students at the University of Massachusetts in 2004 and 2005. Most differences between the beginning and end of the semester were significant (*, P<0.05; †, P<0.01).*

TABLE 1
Student Creativity Survey

Rate the following as best as possible:

	strongly agree				strongly disagree
1. I feel confident developing novel ideas and concepts	1	2	3	4	5
2. Based on my previous educational experience, I feel that I have the skills necessary to generate novel ideas and concepts	1	2	3	4	5
3. When assigned an poorly defined, open-ended task I eagerly start generating ideas	1	2	3	4	5
4. I enjoy finding solutions to difficult problems	1	2	3	4	5
5. I enjoy formulating concepts to describe how things work	1	2	3	4	5
6. I have trouble generating unique ideas because I don't like the quality of the ideas I generate	1	2	3	4	5
7. I have trouble listing more than three unique ideas when faced with open-ended assignments	1	2	3	4	5
8. I prefer problem-solving to tackling open-ended tasks	1	2	3	4	5
9. Based on my previous educational experience, I feel better prepared to solve specific problems than approach open-ended tasks	1	2	3	4	5
10. I often brainstorm when finding solutions to problems	1	2	3	4	5
11. When solving problems, I evaluate ideas as I generate them	1	2	3	4	5
12. I usually generate a series of possible ideas before evaluating them	1	2	3	4	5

EVALUATION OF STUDENT CREATIVITY

For two sequential years (2004 and 2005), surveys were used to evaluate student confidence with engineering creativity in the first-year chemical engineering course at the University of Massachusetts (Table 1). Students were asked to rate whether they strongly agreed (1) or strongly disagreed (5) with the twelve statements in the survey. These surveys were administered at the beginning of the semester (before any discussion of creativity) and at the end of the semester. During the semester, the materials and exercises on engineering creativity were presented. The questions were designed to ascertain students' attitude toward creativity (questions 1, 4, 5, 6, and 8), behavior when required to be creative (questions 3, 7, 11, and 12) and skills at being creative (questions 2, 9, and 10).

Between the beginning and end of both investigated semesters, 10 of the twelve student-responses changed significantly (Figure 5). For all questions, students responded positively about creativity (responses less than 3). The only questions that students disagreed with (questions 6 and 7; responses greater than 3) were worded negatively. Comparing students' responses at the beginning and end of the semester gave an indication of the effectiveness of the presented materials. Over the course of the semester (Figure 5) students gained confidence with generating ideas (question 1; $P<0.05$), felt that they had more skills to generate ideas (question 2; $P<0.01$), more eagerly generated ideas (question 3; $P<0.01$), enjoyed solving difficult problems more (question 4; $P<0.01$), liked the quality of their ideas more (question 6; $P<0.05$), and brainstormed more

TABLE 2
Correlation between questions at beginning of semester[a]

Question	1	2	3	4	5	6	7	8	9	10	11	12
1. Confidence												
2. Skills to generate ideas	0.70 †											
3. Eagerly generate ideas	0.36 †	0.28 *										
4. Enjoy difficult problems	0.37 †	0.35 †	0.21									
5. Enjoy how things work	0.39 †	0.37 †	0.28 †	0.71 †								
6. Don't like ideas generated	-0.30 †	-0.27 *	-0.12	-0.22 *	-0.10							
7. Trouble listing ideas	-0.23 *	-0.25 *	-0.21	-0.24 *	-0.15	0.36 †						
8. Prefer problem solving	0.04	0.11	-0.32 †	0.34 †	0.26 *	-0.08	0.09					
9. Skills to solve problems	0.12	0.08	-0.30 †	0.32 †	0.27 *	0.06	0.15	0.57 †				
10. Brainstorming	0.24 *	0.30 †	0.17	0.24 *	0.29 †	-0.01	-0.14	0.05	0.11			
11. Evaluate while generating	0.26 *	0.23 *	0.17	0.11	0.18	-0.20	-0.05	-0.01	0.00	0.34 †		
12. Generate series of ideas	0.03	-0.04	0.12	0.05	0.14	0.09	-0.10	-0.07	0.01	-0.01	-0.09	

[a]Elements contain the Pearson coefficient and the significance of population correlation coefficient (*, P<0.05; †, P<0.01). The sign of the Pearson coefficient indicates direct (+) and indirect (-) correlation.

TABLE 3
Correlation between questions at end of semester[a]

Question	1	2	3	4	5	6	7	8	9	10	11	12
1. Confidence												
2. Skills to generate ideas	0.58 †											
3. Eagerly generate ideas	0.54 †	0.42 †										
4. Enjoy difficult problems	0.42 †	0.35 †	0.47 †									
5. Enjoy how things work	0.31 *	0.29 *	0.45 †	0.74 †								
6. Don't like ideas generated	-0.43 †	-0.32 *	-0.33 †	-0.06	0.05							
7. Trouble listing ideas	-0.52 †	-0.34 †	-0.24	-0.17	-0.09	0.59 †						
8. Prefer problem solving	0.11	0.22	-0.01	0.46 †	0.43 †	0.31 *	0.17					
9. Skills to solve problems	0.39 †	0.42 †	0.11	0.50 †	0.43 †	0.12	-0.20	0.67 †				
10. Brainstorming	0.52 †	0.39 †	0.31 *	0.46 †	0.36 †	-0.13	-0.29 *	0.28 *	0.47 †			
11. Evaluate while generating	0.28 *	0.18	0.35 †	0.35 †	0.42 †	0.00	0.10	0.43 †	0.36 †	0.36 †		
12. Generate series of ideas	0.12	0.31 *	0.10	-0.03	0.20	-0.15	-0.34 †	-0.08	0.12	0.24	-0.14	

[a]Elements contain the Pearson coefficient and the significance of population correlation coefficient (*, P<0.05; †, P<0.01). The sign of the Pearson coefficient indicates direct (+) and indirect (-) correlation. Shaded cells are significant in Table 3 and not in Table 2.

when solving problems (question 10; P<0.01). Students reported that they enjoyed formulating concepts to describe how things work less (question 5; P<0.01), evaluated ideas as they generated them more (question 11; P<0.01), and generated a series of ideas less (question 12; P<0.01). These three results may reflect increased student understanding about the creative process. After the lectures, they may have had a better understand about what was meant by generating ideas before evaluating them and may be more accurately reporting their behavior. Lastly, students reported that their preference shifted from specific problems to open-ended tasks (question 9). This reflects that the creativity module was successful for those two groups of students.

Pearson correlations between the questions were calculated to determine how individual students felt about creativity and idea generation before exposure to the creativity module (Table 2). The sign of the Pearson correlation indicates direct or indirect correlation between the questions. Significance of the population correlation coefficients indicates 95% (*, P<0.05) and 99% (†, P<0.01) confidence. Many of the initial questions were tightly correlated, indicating that students who were confident about developing ideas (question 1) felt that they had the necessary creativity skills (question 2; Q1-Q2, $P<0.01$) and enjoyed the creative process (question 4 & 5; Q1-Q4, $P<0.01$; Q1-Q5, $P<0.01$). The correlations show that students who don't like the ideas they generate (question 6) have trouble listing more than three ideas (question 7; Q6-Q7, $P<0.01$). Question 12, which asks whether students generate a series of ideas before evaluating them, was not correlated with any other question, including confidence with idea generation (question 1), liking the quality of ideas (question 6), or feeling that they have the skills for idea generation (question 2). This lack of correlation indicates that at the beginning of the course students had not been introduced to the concept of generating ideas before evaluating them.

Many more of the questions were correlated at the end of the semester than at the beginning (Table 3; shaded region). Question pairs with increased correlation indicate changes in student perception and understanding of the creative process. Students reported that generating ideas before solving them (question 12) and brainstorming (question 10) gave them skills to generate ideas (question 2; Q2-Q12, $P<0.05$) and skills to solve open-ended problems (question 9; Q9-Q10, $P<0.05$). These new skills helped students have confidence to develop new ideas (question 1; Q1-Q9, $P<0.01$). Using brainstorming (question 10) and enjoying idea generation (question 6) helped students feel more comfortable with open-ended tasks (question 8; Q6-Q8, $P<0.05$; Q8-Q10, $P<0.05$). Importantly, students who learned to brainstorm (question 10) and generate ideas before evaluating them (question 12) had less trouble listing unique ideas when faced with open-ended assignments (question 7; Q7-Q10, $P<0.05$; Q7-Q12, $P<0.01$).

CONCLUSIONS

The concepts introduced in this engineering creativity module helps students become more comfortable with open-ended problems. With these tools they learn how to approach open-ended problems and how to separate idea generation form analysis. The questionnaires administered in an introductory chemical engineering course confirmed that engineering creativity can be enhanced. The surveys showed that learning how to brainstorm and generate ideas independent of analysis reduces students' difficulty with ambiguous tasks. The results also showed that practice with creative exercises increases confidence with novel idea generation. Students who brainstormed had more success with open-ended problems and students that liked their ideas more effectively generated many ideas. While creativity is difficult to teach explicitly, creating a defined space for students to practice these skills clearly enhanced their abilities.

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