Evaluation of creativity and problem solving in chemical engineering education

Neil S. Forbes
Assistant Professor
Chemical Engineering
University of Massachusetts, Amherst

Creativity is essential for successful engineering; it is necessary for all technological advancement, and is highly correlated with economic prosperity and success [1,2]. Creativity and innovation play a role in most levels of engineering education, and yet they are rarely discussed explicitly in 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] .

Here I describe a series of projects, lectures and exercises designed to enhance student creativity. These components were intended to be a part of an introductory freshman course. At UMass this course, Engin110, was created to introduce first-semester freshman to chemical engineering and encourage their participation in the field. This course teaches the basics of mass balance and engineering economics, the use engineering software, elementary process design, ethics, and the careers paths available to chemical engineers. The structure and timing of this course makes it an excellent opportunity within the curriculum to introduce the importance and role of creativity in engineering.

Table 1 outlines the schedule of topics in the introductory course at UMass. In bold are the items, described here, that were added to foster creative engineering. Two lectures were added to the course to define engineering creativity; discuss how to dissect a problem; and how to generate ideas. Two open-ended projects were assigned in the course: a literature research project and a group process design project. A series of in-class exercises provided a defined period of time for students to practice creative idea generation. In addition, evaluations were included to assess student confidence with open-ended problems before and after instruction.

Table 1. Lecture topics in Introduction to Chemical Engineering

Introduction	***Lecture II: Developing ideas; library and research skills***	*Economics (four lectures)*
History of chemical engineering	*Technical writing*	***Individual process designs***
Process design (two lectures)	***Peer review of research abstracts***	*Faculty research panel*
Research project assigned	*Mass balances (three lectures)*	*Computer skills (three lectures)*
Lecture I: Definition of engineering creativity; in-class creativity exercise; initial creativity survey	*Computer skills (three lectures)*	***Group design presentations II***
	Group design presentations I	*Ethics*
		Final creativity survey

Within the first engineering creativity lecture, students were introduced to the concepts, described below, designed to enhance creativity. Students were also be taught 1) how to divide problems into the two steps of a) idea generation and b) idea analysis by defining goals and constraints; 2) how to research facts and methods to define the constraints of the brainstorming space; 3) how to determine from the goals whether a problem is interpolative or extrapolative (defined below); and 4) how to overcome the physiological “fear of a blank page” that extrapolative problems induce by treating them similarly to interpolative problems.

Here, I define two modes of engineering creativity: interpolative and extrapolative. *Interpolative creativity* is the creation of connections between known facts using established methods to arrive at concrete goals. *Extrapolative creativity* is an outgrowth from a set of facts using discovery and development of new methods towards less clearly defined goals. Interpolative creativity, or problem solving, is more commonly discussed in engineering courses and is more comfortable for most engineers. Within the life sciences, however, extrapolative creativity is more highly regarded as demonstrated by the emphasis placed on hypothesis generation. Commercial innovation is also open-ended and requires extrapolative creativity. Both modes of creativity utilize a similar set of skills. Demonstrating the similarities of the modes encourages students to utilize their problem solving skills to generate strong hypotheses and innovative business plans as well as effectively solving engineering problems.

Using these educational tools and surveys I tested the hypothesis that purposely constructed classroom lectures and projects can be used to enhance student creativity. There is debate in the literature about whether creativity can actually be taught [1,6,7]. Creativity in engineering is dependent on many factors, including innate ability, experience, and good mental habits [6,8]. While some students have more innate ability and experience from which to draw, many students fall into mental traps that limit their creative potential. By censuring their more outlandish ideas many talented students seem to limit their creativity before they can fully flesh out their ideas.

Engineering creativity can be broken down into two distinct steps: idea generation and idea analysis. Idea generation is also referred to as lateral thinking [9,10] or brainstorming [11,12]. Idea analysis is a skill that engineers are well trained in, and includes, for example, evaluation of physical correctness, feasibility, or profitability. By observing the best students it appears to me that successful idea generation is dependent on the number of ideas formed and the ability to generate ideas independent of analysis. Generating a large number of ideas, regardless of their quality, increases the likelihood that an innovative concept were discovered [6,8,13,14]. Students who struggle with open-ended problems often try to combine idea analysis and generation. Successful idea generation requires that the two steps be performed separately [4,6,13,14]. 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. This means that the most tangential and innovative ideas are often ignored.

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 [4,6,14,15], including brainstorming [11,12], synectics [16,17] and lateral thinking [9,10]. Reading and exposure to experiences outside of engineering often enhances creativity [18]. A creative environment encourages independent thinking, self-awareness, openness to experience, and breadth of vision [15,19]. From my experience, creative ideas come from students who can relate their personal experience and current knowledge base to the problem at hand.

Research project The first major assignment in the course was an extrapolative literature research project. For this project students were asked to identify a technology or social issue that impacts or is impacted by chemical engineering. The students were encouraged to identify topics that are personally significant to them. They were also asked to generate a novel idea regarding their topic, i.e., a new technology or application of engineering principles; this is the creative element of the project.

When first introduced, students were not be given any specific guidance to help generate novel ideas. May students had difficulty with this assignment. Generating new technical ideas is a skill that students are not exposed to in a typical high school education. After allowing students time to struggle with creative idea generation independently, lectures and exercises on creativity were presented. Surveys were distributed to evaluate each student's perception of their own creativity prior to any instruction. These surveys are described in detail below.

Students were then asked to return to the task of generating novel ideas. They were encouraged to use literature-survey and brainstorming skills taught in class. Students generated abstracts, which were peer reviewed, and produced a moderate length paper (3-5 pages) in which they developed their ideas more fully. At the end of the project, students were surveyed again to determine whether they perceived an increase in their creative abilities.

In-class creativity exercise In-class exercises were used to provide defined time in class for students to practice creative problem solving. Many of the creative exercises presented in the literature are open-ended (extrapolative) [5,14] or are small brain teasers (interpolative) [6,7]. To illustrate idea generation and analysis, a small interpolative problem was used. By using a concrete problem students could observe how physical constrains put bounds on the brainstorming space and how physical properties could be used to test ideas.

A geometric problem in which the shape of a design affects its behavior and that has many possible solutions meets the above criteria for an illustrative exercise. One example is the design of column packing. There are many varying and competing designs and shapes currently on the market. In most cases the shape of the packing material was designed to increase gas flow rate while increasing surface area for mass transfer [20,21]. Because the design of column packing is such a complex problem, most of the current designs were determined by experimentation, trial and error, and experience [21]. To render this problem tractable in a single class period it was reduced to two dimensions. Students were given a set of 11 x 11 grids on which to design a series of two-dimensional packing materials that were used to fill a 59 x 51 column. There are an almost infinite number of potential designs on this relatively modest length scale. The best packing materials were defined as those with the highest surface area for mass transfer with the lowest resistance to gas flow once filled into a column. For this problem flow rate was assumed to be proportional to void fraction. Two possible designs, a poor performer (a solid square) and an average performer (a line), were presented to illustrate how geometric design affects these two properties.

Students were given 10 minutes to generate as many packing designs as possible. For each design they provided a reason why it would meet the design criteria. During this period, students were encouraged to not analyze or compare their ideas, but instead to generate as many reasonable designs as possible. This was the brainstorming or idea generation element of the creative process. Once completed, students were asked to rank their designs. Time was provided for the students to develop evaluation techniques. Students were then formed into groups that presented their best idea to the class.

Students were then provided with a stochastic *Visual Basic* simulator to evaluate their designs and compare the results to those based on their own devised evaluation techniques. This simulator, which uses Excel as an interface, filled a theoretical column with packing to calculate the overall void fraction and surface area. Students were encouraged to compare what they thought was their best idea to their worst. This was intended to illustrate the benefit of generating a large number of potential designs. To encourage individual creativity, grades for this exercise were determined mostly by the number of ideas generated and not the performance of the designs.

Design project The second assigned project was an interpolative group design problem. Students were assembled into groups of three or four and given a choice of compounds to produce. Each group gave two presentations regarding their compound. In the first, groups presented the uses of their compound, the history of its production, and its typical annual profit. The groups used this set of information as a springboard to their second presentations in which they described a novel process flowsheet to produce their compound.

To encourage individual brainstorming, students were asked to develop their own process designs and improvements prior to meeting with their groups. They were asked to use the information they gathered as a group for the first presentation as the basis for their ideas. All of their potential designs were handed in and graded based on their quantity and uniqueness, irrespective of their quality or feasibility. Students then prioritized their ideas and shared them with their groups, who integrated them into a single design.

Student feedback and instructor evaluation Questionnaires were used to determine the effectiveness of these techniques, determine students' confidence with open-ended problems, and ascertain how much of the techniques have been learned. The questionnaires probed students for their attitude toward open-ended problems, the skills they have learned for tackling open-ended problems and their behavior when faced with these challenges. All questions were answered on a one to five scale (weak to strong). Example questions are 1) Do you feel confident developing novel concepts based on your educational experience? 2) Based on previous instruction, do you feel that you have the skills to generate novel ideas and solutions to problems? 3) When assigned an open-ended task do you eagerly start generating ideas? The questionnaires were worded in such a way that the same set of questions could be used at the beginning and end of the semester. These evaluations showed that engineering creativity can be enhanced with classroom lecture and projects.

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