Teaching Idea Generation to Undergraduate Students within the Time Constraints of a Capstone Course

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Introduction

One of the challenges in teaching capstone design is fully covering the breadth of numerous techniques at a depth that is beneficial to students in a reasonable time frame. For example, at Penn State Erie we are limited to three 50-minute class periods to teach concept generation. Given this limitation, a balance must be chosen between quantity of the methods taught, and the detail in which students learn them.

In spite of the wide array of ideation methods, undergraduate students often end up implementing only the basic brainstorming method for their capstone projects. The senior design projects in the Mechanical Engineering (ME) capstone program at Penn State Erie, the Behrend College vary widely from traditional mechanism design and construction projects where standard concept generation techniques are appropriate, to design optimization problems with a strong focus on mathematical modeling where concept generation relies heavily on the results of technical analysis and understanding of the technical aspects of the problem. Due to the wide variety of projects in ME capstone program, it is difficult to teach a “one–size fits all” concept generation method. The optimal concept generation method may vary across the different types of design projects. As the concept generation is not limited to full solutions and partial design solutions are accepted, the term idea generation will be used to describe the methods in this paper.

To address these issues, an exploratory study was conducted at Penn State Erie to teach idea generation methods to seniors using peer learning. This study aims to determine preferences across different idea generation methods and the factors that might influence these preferences. This study also investigates whether peer learning is an effective way for teaching a variety of idea generation methods. Finally, the study compares the concepts generated using different methods with an evaluation rubric comprising of quality, quantity, novelty, and variety to determine usefulness of each method at the undergraduate level. Student feedback about the perceived usefulness of each ideation method was collected. The authors believe that it is acceptable if the team decides to implement a blend of methods, choose a single method, or even if each student in the project team applies a different method for idea generation, as long as it fosters creativity.

Research Method

For this study, a population of students were each taught two of a total of eight methods of idea generation in a traditional classroom setting, and were asked to peer teach these methods to their team members. The faculty-led instruction consisted of two class periods, and during a third class period the students participated in the peer learning. During the course of this week, students were asked to apply the idea generation methods to generate design concepts for a common design prompt. These students were asked to evaluate the idea generation methods as well as the ideas generated by their team members with other methods. The sections below explain the study population, idea generation methods taught, study procedure, and the evaluation rubric.
Study Population

The capstone cohort in the ME program consists of 83 Mechanical Engineering seniors. These students were enrolled in two sections (containing 40 and 43 seniors) of the course taught by different instructors. Most of the design projects comprised teams of four students working on an industry-sponsored project. Concept generation was a part of the curriculum so all the students participated in this study. A few students did not attend all three days; therefore, a few teams could not complete all the assigned activities.

The senior design class was divided into four ‘idea sections’ such that each project team member was in a different idea section and each project team member learned a different idea generation method. Since all idea sections were conducted at the same time, four different faculty members taught each section. All the faculty members teaching idea generation had prior experience in teaching the engineering design process. Within the idea sections, teams of four students were formed which are referred as ‘concept teams’ throughout the paper. The students worked with their concept teams in the idea sections for the duration of the study. The ‘project team’ refers to the actual senior design project teams to avoid confusion with ‘concept team’.

Idea Generation Methods

The ideation methods that were covered in this study were brainstorming, collaborative sketching, mind-maps, morph matrix, design by analogy, TRIZ, bio-inspired design, and 77 design heuristics for inspiring ideas. Shah et al. presents a very good summary of all idea generation methods. Table 1 shows the idea generation methods that were taught to each idea section as an initial method and as a method to kick-start creativity when the students feel stuck. Brainstorming and TRIZ were traditionally taught at Penn State Erie. Collaborative sketching or modified 6-3-5 is another effective group brainstorming method that students seem to appreciate. Design Heuristics 77 cards for inspiring ideas has shown promising results for idea generation. Bio-inspired design methods and design by analogy using word tree are also known to promote creativity. Mind maps and morph matrix are other common methods used for idea generation.

Idea Generation Study Protocol

The study was split over three 50-minute class periods and conducted in one week on Monday, Wednesday, and Friday. In the first class period, a method to initiate idea generation was taught, and the students (concept teams) were given time to implement it for a common design prompt. A method to kick-start ideation was taught in the second class period and students (concept teams) continued to generate ideas for the same design prompt. In the third class period, students in each project team rated the ideation results of their peers who were in a different concept team. They also discussed and compared the ideation methods with their project teams, and filled out a survey at the end.
Table 1. Idea generation methods taught to each idea section as an initial method and to kick start creativity when the students feel stuck

<table>
<thead>
<tr>
<th>Idea Section</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial method</td>
<td>Morphological Matrix</td>
<td>Mind Maps</td>
<td>Brainstorming</td>
<td>Collaborative Sketching</td>
</tr>
<tr>
<td>Kick-start creativity</td>
<td>77 card for Inspiring ideas</td>
<td>Bio-inspired Design</td>
<td>TRIZ</td>
<td>Design by analogy</td>
</tr>
</tbody>
</table>

On the first day, students were introduced to the topic of idea generation and to the overall study procedure. In the introduction, students were instructed about what idea generation is, the importance of idea generation, and how to generate ideas. The evaluation of idea generation using the rubric based on quantity, quality, novelty, and variety was also explained. The introduction to idea generation was followed by the design prompt, which is presented in the Appendix. The design task given to the student was to create a push-assist device for bariatric wheelchairs. The design prompt included the background, the objective tree, the function structure, and the engineering specifications; these topics were taught in the previous lectures. The same design problem was previously used as an example while teaching other steps in the design process, so the students were already familiar with the problem statement. After the introduction to the design prompt, each instructor taught the section-specific idea generation method, as shown in Table 1, to help students get started with ideas. Students continued working on the idea generation for rest of the class period. Students were instructed to sketch the ideas and to come up with as many ideas as possible.

At the end of the first class, students were assigned an individual homework assignment to continue working on the idea generation outside of class and bring it to the following class period. Studies have shown that creative thinking is not a one step process but it involves multiple stages including preparation, incubation, and illumination. Students were instructed to allow a few hours away from the design problem, and then jot down the ideas that they came up with.

The second day began with a discussion on how students might feel stuck or unable to come up with more ideas. Similar to the first day, each instructor in the idea sections taught the section-specific idea generation method that would help to kick-start creativity. The students continued idea generation with the second method for rest of the class period. At the end of second class period, students were told to continue working with their concept team outside the class until the team ran out of ideas. All the ideas from the team, including the individual ideas, were collected at the end of the study. Students also were asked to make additional copies of their group’s ideas so that each of the concept team members could bring it to next class.

On the final day of the study, the students met with their original project teams. Each of the project team members had been in a different idea section from the others. The project team then
swapped the four packets of generated ideas such that each member got to evaluate the ideas of two of their other project team members, resulting in each concept generation packet having ratings from two members of the project team. The evaluation method used to rate ideas is explained further in Table 2. As this process was repeated for each member of the concept generation team, (4 members), each idea packet was evaluated by 8 different students. Two of the instructors also evaluated the idea packets from all 21 concept teams.

After the evaluation of ideas, the project team was given time to discuss all the idea generation methods that their peers learned. At the end of the discussion, students filled out the feedback survey. The survey asked questions about preferences: which methods they liked and which methods they plan to apply to their projects. The last day was concluded with a brief wrap up of the do’s and don'ts for concept generation.

Evaluation

The ideas generated by the concept teams were evaluated using the rubric shown in Table 2. The evaluation rubric is based on the ideation metric used to evaluate ideas \(^1,13\). We have adopted a simpler version of the ideation metric in our design courses to emphasize four factors, namely, quality, quantity, novelty, and variety that aptly represent idea generation. The original ideation metric is difficult to implement within the time constraints and resources available for a senior level course. Both the faculty and the students evaluated the idea generation using the same evaluation rubric.

Creativity is higher when the designer creates a large number of feasible ideas. While a large number of creative ideas is desirable; some novice designers, such as the senior design students, lack the maturity to come up with at least a few feasible ideas. In our experience, some senior design students tend to deviate from the main design task towards many impractical ideas that may not serve the overall goal of concept generation. To avoid this issue, the faculty at Penn State Erie emphasize the importance of generating at least a few feasible ideas that are realistic.

Measurement of quantity is straightforward and direct. However, the measurement of quality, novelty, and variety is more involved. The quality factor in the rubric emphasizes the importance of generating feasible ideas while the novelty factor emphasizes the importance of out-of-the-box thinking. On the same lines, the variety factor on the rubric emphasizes the importance of exploring the design space. This adaptation of the original ideation metric in form of a rubric is currently a work-in-progress and will be adjusted appropriately in the future based on the feedback received from faculty at Penn State Erie as well as other researchers. The results of idea generation from the students, based on the implementation of this rubric, also provides a valuable feedback on the clarity of rubric itself.
Table 2. Evaluation Rubric used to evaluate idea generation

<table>
<thead>
<tr>
<th>Metric</th>
<th>0 point</th>
<th>1 point</th>
<th>2 point</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong> QUANTITY</td>
<td>Few (n ≤ 10) concepts generated. Very few functions considered</td>
<td>Some (10 &lt; n ≤ 20) concepts generated. Most functions considered</td>
<td>Lots of concepts (n &gt; 20) generated. All functions considered.</td>
<td></td>
</tr>
<tr>
<td><strong>2</strong> QUALITY</td>
<td>None of the concepts generated are feasible in the context or practical</td>
<td>Some of the concepts generated are feasible in the context or practical</td>
<td>Most of the concepts generated are feasible in the context or practical</td>
<td></td>
</tr>
<tr>
<td><strong>3</strong> NOVELTY</td>
<td>No innovative concepts. No thinking outside the box. All concepts are obvious and typical.</td>
<td>At least 2-3 concept innovative or outside the box. Several concepts at the edge of the box.</td>
<td>Several innovative concepts. Thinking &quot;outside&quot; the box. High-risk and new ideas.</td>
<td></td>
</tr>
<tr>
<td><strong>4</strong> VARIETY</td>
<td>No variety in generated concepts. Design space not explored.</td>
<td>Some or slight variety in generated concepts. Design space somewhat explored</td>
<td>Significant variety in generated concepts. Design space thoroughly explored</td>
<td></td>
</tr>
<tr>
<td><strong>5</strong> OVERALL</td>
<td>Concept generation was poorly done and is unacceptable. No sketches.</td>
<td>Some effort was put into the concept generation process, but there is room for improvement. Few sketches</td>
<td>Concept generation was well done. Looks almost complete. Sketches and labels used effectively</td>
<td></td>
</tr>
</tbody>
</table>

**TOTAL POINTS (10 maximum)**

Results and Discussion

The ideas generated by the concept teams in each idea section were evaluated using the evaluation rubric shown in Table 2. The effectiveness of different idea generation methods was then compared using the quantity, quality, novelty, and variety scores given by the faculty and students to concept teams in each idea section. Nonparametric comparisons for each pair of idea section conducted using Wilcoxon method (at α = 0.10) for quantity, quality, novelty, and variety based on both faculty and student evaluations is tabulated in Table 3.

Idea Section A covered morph matrix and 77 cards for inspiring ideas. The quantity of ideas generated by all the concept teams in this section was significantly higher than all other sections. This observation was true for both the student evaluations as well as the faculty evaluations. Figure 1 displays the proportion of quantity score 0, 1, and 2 of all concept teams. The 77 cards for inspiring ideas seemed to produce more ideas as each of the cards act as a prompt for a new idea. Morph matrix also helps to explore the design space by focusing on one function at a time. The combination of the two methods in Idea Section A possibly led to higher quantity of ideas. Consequently, the higher number of ideas led to ideas with greater variety.
Table 3. Nonparametric comparisons for each pair of idea section conducted using Wilcoxon method (at \(a= 0.10\)) for quantity, quality, novelty, and variety based on both faculty and student evaluations

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Faculty Evaluation</th>
<th>Student Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Score Mean Difference</td>
<td>Standard Error Difference</td>
</tr>
<tr>
<td>Idea Section</td>
<td>Idea Section</td>
<td></td>
</tr>
<tr>
<td>B A</td>
<td>-8.90</td>
<td>2.32</td>
</tr>
<tr>
<td>C A</td>
<td>-7.90</td>
<td>2.28</td>
</tr>
<tr>
<td>D A</td>
<td>-5.90</td>
<td>2.13</td>
</tr>
<tr>
<td>C B</td>
<td>0.80</td>
<td>2.01</td>
</tr>
<tr>
<td>D B</td>
<td>1.70</td>
<td>2.32</td>
</tr>
<tr>
<td>D C</td>
<td>0.90</td>
<td>2.37</td>
</tr>
<tr>
<td>Quality</td>
<td>Faculty Evaluation</td>
<td>Student Evaluation</td>
</tr>
<tr>
<td>Idea Section</td>
<td>Idea Section</td>
<td></td>
</tr>
<tr>
<td>B A</td>
<td>-5.10</td>
<td>2.32</td>
</tr>
<tr>
<td>C A</td>
<td>1.10</td>
<td>2.38</td>
</tr>
<tr>
<td>D A</td>
<td>0.00</td>
<td>2.39</td>
</tr>
<tr>
<td>C B</td>
<td>5.30</td>
<td>2.28</td>
</tr>
<tr>
<td>D B</td>
<td>4.40</td>
<td>2.21</td>
</tr>
<tr>
<td>D C</td>
<td>-0.90</td>
<td>2.28</td>
</tr>
<tr>
<td>Novelty</td>
<td>Faculty Evaluation</td>
<td>Student Evaluation</td>
</tr>
<tr>
<td>Idea Section</td>
<td>Idea Section</td>
<td></td>
</tr>
<tr>
<td>B A</td>
<td>-1.40</td>
<td>2.33</td>
</tr>
<tr>
<td>C A</td>
<td>-4.70</td>
<td>2.46</td>
</tr>
<tr>
<td>D A</td>
<td>-5.30</td>
<td>2.49</td>
</tr>
<tr>
<td>C B</td>
<td>-3.80</td>
<td>2.48</td>
</tr>
<tr>
<td>D B</td>
<td>-4.60</td>
<td>2.52</td>
</tr>
<tr>
<td>D C</td>
<td>-1.70</td>
<td>2.30</td>
</tr>
<tr>
<td>Variety</td>
<td>Faculty Evaluation</td>
<td>Student Evaluation</td>
</tr>
<tr>
<td>Idea Section</td>
<td>Idea Section</td>
<td></td>
</tr>
<tr>
<td>B A</td>
<td>-6.20</td>
<td>2.32</td>
</tr>
<tr>
<td>C A</td>
<td>-8.10</td>
<td>2.45</td>
</tr>
<tr>
<td>D A</td>
<td>-7.20</td>
<td>2.41</td>
</tr>
<tr>
<td>C B</td>
<td>-3.50</td>
<td>2.12</td>
</tr>
<tr>
<td>D B</td>
<td>-0.90</td>
<td>2.01</td>
</tr>
<tr>
<td>D C</td>
<td>2.50</td>
<td>2.21</td>
</tr>
</tbody>
</table>
Figure 1. Faculty and student evaluation of the quantity of ideas generated by the concept teams

Idea Section A also had significantly higher variety of ideas according to the faculty evaluation. The proportions of variety score 0, 1, and 2 for both faculty and students is shown in Figure 2. Student did not seem to notice the difference in the variety score. Student evaluators probably required more training on the thorough exploration of design space for solutions before rating the idea packets for variety. Providing a range of solutions for each function of the design prompt could have helped the student evaluators to evaluate the ideas on the variety scores better.

Figure 2. Faculty and student evaluation of the variety of ideas generated by the concept teams

The Idea Section B was taught mind-maps and bio-inspired design methods. The quality of the ideas generated by the concept teams in Idea Section B was significantly lower than all other sections as shown in Figure 3. This difference was observed both by the faculty and student evaluators. The possible reason for lower quality in bio-inspired methods might be that the students did not find the direct application of bio-inspired design for the design of wheelchair push-assist device.
For the novelty scores, Idea Sections C and D were lower than Idea Sections A and B, as shown in Figure 4. Similar to variety, the evaluation by students on novelty scores showed no significant trend. As was seen in the variety, the difficulty of quantifying novelty scores may have accounted for the lack of significant trends in the student evaluations data. According to the faculty evaluations, Idea Section A had significantly higher novelty than Idea Sections C and D. Also, Idea Section B had significantly higher novelty scores than Idea Sections D as per faculty evaluations.

Student feedback was collected at the end of the study, and is presented in Figure 5. There was a mixed response from the students about the benefits of learning the idea generation methods. This study also investigated whether peer learning is an effective way for teaching a variety of idea generation methods to students in a short amount of time. When the students were asked if they discussed the methods with their peers and whether they understand the methods taught by their peers; the student response was much more positive. This result indicates that peer learning might be a possible way to teach a variety of idea generation methods to undergraduate students within a limited time frame.
This study also aims to determine student preferences across different idea generation methods. Figure 6 shows the percentage of students that ‘like’ each of the methods. Similarly, Figure 7 shows the percentage of students who plan to ‘apply’ each of the idea generation methods for their senior design project. Students seem to prefer brainstorming and TRIZ significantly more (p-value < 0.05) as compared to any other methods.
The experience level of the faculty teaching the methods may have influenced the preference for different methods. Idea Sections A, B and D were instructed by three faculty members who had less than two years of teaching experience. Furthermore, a faculty member with more than 20 years of experience taught brainstorming and TRIZ to Idea Section C. This difference in the faculty level of experience could have biased the students’ preference of the idea generation methods.

Summary

The application of theory to practice is often challenging. This study aimed to explore what the best approach is to teach idea generation methods to students within the time frame of a capstone course. This is a work in progress and it gives us a very good insight into teaching concept generation to undergraduate students. Overall, the students seem to appreciate learning different methods for idea generation. The results of this study can help capstone instructors to better plan teaching concept generation.

The preference of idea generation methods from the students did not correlate with the quality of design output. Specifically, the students did not appreciate the 77 cards for inspiring ideas and morph matrix method, but these methods helped produce better quantity, quality, and variety of ideas. Bio-inspired methods may have been hindered by the short time of instruction, or could be perceived as more useful for a different design prompt. Students seem to favor brainstorming and TRIZ, however these methods did not produce the best results for idea generation in this study.

At this point the effect due to each individual method cannot be separated. Future work includes plans to design a study for the impact of each individual method separately, with a wider variety of design prompts. The effect of different idea generation methods on the student projects will be
quantitatively tracked. Future studies will also be designed to limit any bias due to faculty experience. Overall, the study showed that different design methods can be taught to students using both instructor and peer learning, and that these methods can positively affect student creativity.

References


Appendix

The design prompt of the wheelchair push-assist device that was provided to the students for this study is presented below. The objective tree, function structure, and engineering specifications related to the wheelchair push-assist device are taught in the lectures before teaching concept generation.

Wheelchair push assist device

Background: Bariatric is the branch of medicine that deals with causes, prevention, and treatment of obesity. Generally refers to people weighing 350 lbs. or more (typical is 550 lb). Most of these people cannot walk and need a wheelchair. Medicare patients are not eligible for motorized wheelchair and have to be pushed.

Normal wheelchair: Maximum weight of 250 lb.
Normal width 26-28 in.
Bariatric wheelchair: Average weight of 550 lb.; up to 1,000 lb.
Width ranges from 34 to 40 inches

Due to weight and width of handles, it is difficult for normal adults to push bariatric wheelchairs. This difficulty creates workplace injuries to the lower back, hips and shoulders. The goal is to develop a device that will reduce work-related injuries for people pushing bariatric wheelchairs. The device should be portable and interchangeable and attach to the back of the wheelchair.

Problem statement: Design a portable wheelchair push-assist device that could be attached to a bariatric wheelchair to reduce strain on operator’s body.

Objective Tree:

- Reduces probability of injury
  - Minimal strain on body
  - Allows for easy handling of wheelchair
  - Comfortable to user
    - Ergonomic design
    - Safe: Meets OSHA regulations
- Operates in nursing home environment
  - Goes around corners
  - Goes up and down ramps
  - Works on different floor surfaces
- Portable
  - Lightweight
  - Capable of being easily stored
- Easy to attach
  - No tools needed
  - Attaches quickly
  - Does not damage wheelchair
- Adjustable
  - Width for different size wheelchairs
  - Height for different size operators
- Affordable
  - Costs less than $100 (retail)
  - Low volume production
- Durable
  - Won’t deflect too much or break under load
  - Can survive a drop
Function Structure:

Design a push assist device for bariatric wheelchair to reduce strain on operators' body

Design a push assist device for bariatric wheelchair to reduce strain on operators' body

Engineering Specifications:

<table>
<thead>
<tr>
<th>Marketing Spec</th>
<th>Engineering Specs</th>
</tr>
</thead>
</table>
| 1. Device should reduce the risk of injury | 1a. The device should allow the user to push a bariatric wheelchair without extending their hands more than 6” out from the side.  
1b. The device should allow the user to push a bariatric wheelchair with straight posture (without bending over). |
| 2. Device operates in nursing home environment | 2a. The device allows wheelchair to go around corner with a turning radius of 2.5 ft (from ADA guidelines)  
2b. Goes up and down ramps with a ratio of the height to the length. 1:12 (from ADA guidelines).  
2c. Works on both pavements and indoor non-slip floor surfaces |
| 3. The device should be portable | 3a. The device should weigh less than 15 lb.  
3b. The device fits in a box of 3ft X 1 ft X1ft |
| 4. The device should be easy to install and uninstall | 4a. The device shall not require tools for attaching it to the wheelchair  
4b. The device should able to be installed or uninstalled in less than 60 seconds. |
| 5. The device should be adjustable | 5a. The device should be able to attach to wheelchairs with widths of between 36 and 48 inches  
5b. The device should be adjustable vertically to heights between 36 and 50 inches above the floor |
| 6. The device should be affordable | 6a. The total manufacturing cost of the device should be less than $100 in low volume production |
| 7. The device should be durable | 7a. The device should not yield when a load of 300 lb. is applied at any point in any direction |