Using Concept Maps to Assess Student Learning in a Multi-Section Introduction to Engineering Course

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Introduction

This Evidence-based Practice paper describes the use of a simple concept map assignment to create a foundation for productive faculty conversations across multiple engineering disciplines regarding student learning and pedagogical approaches in a required introduction to engineering course. The authors are part of a team of professors who teach sections of an introduction to engineering course at Lafayette College that is required of all first-year engineering students. While the course has common student learning outcomes that apply to multiple areas of engineering (e.g., that students will understand the engineering design process), each section of the course may take different pedagogical approaches to achieving those outcomes. In addition, each professor selects his/her own topic and adds specific student learning outcomes to the common outcomes that are related to his/her area of disciplinary expertise. The sections of the course that serve as the foundation for the work presented in this paper are taught by faculty members in chemical engineering, civil engineering, and mechanical engineering.

The authors are motivated by a desire to understand how the different approaches faculty use in this introductory course impact student learning. In a pilot project in fall 2015, the authors used a simple concept map assignment, given on the first and last day of each section, to evaluate student learning in the course [1]. This pilot project compared student learning in two sections of the course taught by faculty in the same engineering discipline but with different student learning outcomes. The authors found the exercise to be a useful way to understand student learning in relation to the overall and specific student learning outcomes for each of their sections as well as variations in student learning across the two course sections. The latter proved to be a useful foundation for in-depth discussions regarding the different pedagogical approaches used by the authors. The work led to the development of multiple recommendations for improvements in both course sections.

In fall 2017, the authors invited all faculty who were teaching sections of the introductory course to use the concept map assignment so that the results could be used to compare student learning across sections of the course offered by faculty members in different engineering disciplines, and to facilitate discussions of the different approaches taken in teaching the course as well as identification and sharing of best practices. This paper describes the process and outcomes of the larger project, with a focus on how such an approach can be used more broadly in the analysis and general assessment of introductory engineering courses.

Background

At Lafayette College, the Introduction to Engineering course is required of all engineering majors, and most students take it in their first semester on campus. It has evolved over the years based on changes in desired outcomes for the course as well as enrollment pressures. Prior to Fall 2010, the course introduced students briefly to each of the four BS Engineering majors offered on campus. However, there were no lasting outcomes expected beyond a desire for
students to be better able to choose a major, and enrollment pressures made continuing the structure infeasible going forward. In Fall 2010, a completely new version of the course was introduced, in which students applied a variety math concepts to engineering problems in different disciplines. This model turned out not to be a good fit for our campus because of the large distribution in the math backgrounds of incoming students. Thus, in Fall 2014 the course was again overhauled, this time to introduce students to design in two different contexts.

Currently, the Introduction to Engineering course consists of two topical engineering modules, a graphics module, and a series of co-curricular requirements. The co-curricular requirements are designed to help students determine a choice of major (students are not required to choose until the spring semester) as well as to inspire them about engineering, and the graphics module develops their graphical communications skills and facility with different types of visualization software. The topical engineering modules introduce students to engineering design in two different contexts, typically in two different disciplines. It should be noted, though, that a particular module is likely only to introduce students to a small slice of the engineering discipline – the focus is on design.

The learning outcomes for the course as a whole are as follows:

Upon completion of this course, students will:
• recognize that engineering at Lafayette College and beyond is innovative and exciting
• understand the engineering design process

In support of the outcomes listed above, students will:
• have had an introductory design experience
• have had experiences using engineering equipment, tools, software, and hardware appropriate to the topic of the course
• have a working knowledge of engineering graphics and basic CAD skills
• have an introductory understanding of the societal context of engineering relevant to the topic of the course
• gain experience in visually and orally conveying engineering information, e.g., create and present a poster

In Fall 2017, twelve sections of the course were taught by nine different faculty members. Of those, seven faculty members and eight modules are represented in this study. The departments represented are Chemical and Biomolecular Engineering, Civil and Environmental Engineering, and Mechanical Engineering.

Table 1 shows the title, “home” department, and learning outcomes for each of the modules represented in this study. Appendix A includes brief module descriptions.
<table>
<thead>
<tr>
<th>Module Title</th>
<th>Department</th>
<th>Learning Outcomes</th>
</tr>
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<tbody>
<tr>
<td>Powering the World: Engineering Design &amp; Energy</td>
<td>Chemical and Biomolecular</td>
<td>• Demonstrate the use of the engineering design process as it relates to energy technologies, • Discuss the need for innovative solutions to the global energy challenge, • Analyze the trade-offs between economic and regulatory constraints as well as societal and ethical considerations for energy production, and • Communicate technical ideas about energy production to a general audience</td>
</tr>
<tr>
<td>(Instructor 1)</td>
<td>Engineering</td>
<td></td>
</tr>
<tr>
<td>Powering the World: Engineering Design &amp; Energy</td>
<td>Chemical and Biomolecular</td>
<td>• Gain a better understanding of what chemical engineering is about • Connect the engineering design process to energy issues. • Develop and/or improve their ability to create and present oral presentations.</td>
</tr>
<tr>
<td>(Instructor 2)</td>
<td>Engineering</td>
<td></td>
</tr>
<tr>
<td>Blazing a Path to Design (Instructor 3)</td>
<td>Civil and Environmental Engineering</td>
<td>No module-specific outcomes</td>
</tr>
<tr>
<td>Designing the Sustainable City (Instructor 4)</td>
<td>Civil and Environmental Engineering</td>
<td>• Describe and discuss ways in which engineering has changed / has the potential to change the world; • Explain one approach to the engineering design process and apply it; • Discuss ways in which designing civil infrastructure differs from design of other types of engineering artifacts; • Discuss what it means for a city to be sustainable and apply these considerations in the design process; and • Communicate graphically, in writing, and orally regarding the above.</td>
</tr>
<tr>
<td>Engineering Failures: Lessons for the future</td>
<td>Civil and Environmental Engineering</td>
<td>• Demonstrate a basic knowledge of geotechnical engineering; • Develop a simple model related to the performance of a structure; • Conduct a simple analysis of risk; and • Understand the purpose and format of a geotechnical report</td>
</tr>
<tr>
<td>(Instructor 5)</td>
<td>Engineering</td>
<td></td>
</tr>
<tr>
<td>Design Thinking (Instructor 6)</td>
<td>Mechanical Engineering</td>
<td>• Express the role of engineering in society; • Identify challenges that can be addressed through engineering technology; • Design and iterate upon a solution to an engineering problem; • Deliver a scientific oral presentation; • Integrate ethics into their engineering design practice; • Work collaboratively on a design team;</td>
</tr>
<tr>
<td>Design Thinking (Instructor 7)</td>
<td>Mechanical Engineering</td>
<td>• Identify challenges that can be addressed through engineering technology • Organize knowledge and enumerate design alternatives • List the mission components of a space mission design • Identify spacecraft subsystems and their function • Calculate position and velocity of a satellite in an orbit • Use the rocket equation to relate delta-v and fuel requirements • Use MATLAB/CAD/other software to aid in analysis of your design • Evaluate and apply a Fermi approach to conceptual design problems to create reasonable simplifying assumptions • Evaluate and interpret, and distinguish the assumptions and approximations made in modeling real problems; evaluate appropriateness of assumptions. • Evaluate and perform the engineering design process • Learn to effectively communicate by working collaboratively on a design team • Learn to effectively communicate by delivering a scientific oral presentation</td>
</tr>
</tbody>
</table>
Methods

Concept maps organize information graphically. They were first developed and used as a pedagogical tool in biology by Stewart et al. [2]. In developing a concept map, a student writes down terms that come to mind as the result of a prompt and connects them with directional arrows and text describing the nature of the connections. If the concept maps are to be used to assess or evaluate student learning, the instructor must decide not only how to construct the assignment prompt but also how to evaluate the map. Per [1], in engineering education, concept maps have been used to assess knowledge integration across an engineering program [3], conceptual understanding in an engineering dynamics course [4], and student preconceptions in an introductory transportation engineering course [5], among other applications.

In a pilot project [1], students were asked to develop a concept map on the first day of class in response to the prompt, “What is engineering” (Figure 1 shows the assignment) and were asked to construct a new map using the same prompt on the last day of class. The authors then used a common rubric focused on desired student learning outcomes to evaluate changes between the initial and final concept maps and created radar plots to display the results. Both authors were struck by differences in what we had expected to see and what students actually reported, as well as by how strongly students reflected some of what we tried to teach them. The analysis of the maps and resulting radar plots resulted in several reflective conversations between the authors about the course, our respective modules, what we observed in our students’ concept maps, and what we would hope to observe. These conversations were helpful enough that the authors decided it would be valuable to include more of the course instructors in the project to stimulate a broader conversation across departments about the course.

Subsequently, one of the authors experimented with a slightly modified version of the exercise in which at the end of the module rather than asking the students to construct a new concept map, the instructor returned to the students their original concept maps and asked them to add new ideas or concepts in green pencil. This technique made it easier and less subjective to identify changes in the student maps. The author then collected the added words in a list (repeating words that were used multiple times in a single map and across all the students’ maps in the course) and created a word cloud of the result.

A word cloud is a picture composed of the words used in a piece of text in which each word appears once and the size of each word is proportional to the number of times that word occurs in the text. By creating a word cloud of the words added to the maps by students in the class, the author was able to easily see the relative frequencies of each of the words that students used to modify their original concept maps.

For the current project, the study was expanded to include seven faculty members from three different departments. In each course section, students were asked to construct a concept map on the first day of class using the same set of instructions as in the previous study (Figure 1). On the last day of class (or in some cases on the penultimate day of class) students were given a green pencil and were asked to modify their initial maps on the basis of what they had learned about engineering since the start of the module. The students’ concept maps for all the sections participating in the project were then collected and given to the authors.
Concept Map Assignment

Concept maps are drawings that illustrate relationships between ideas and/or concepts and are often used by designers, engineers, and technical writers to organize their knowledge of a subject—they are a visual method of organizing information. In a concept map, each word or phrase connects to another and links back to the original idea or concept. Concept maps are often used by students to organize information in a course in order to study for a test and they can also be assigned by instructors to assess both the students’ knowledge coming into a program or course and their developing knowledge of course material during and/or at the end of the course.

An example of a concept map is shown below (Novak and Canas, 2008)

For this assignment, I want you to develop a concept map for “Engineering” (i.e., a map that answers the question, “What is Engineering?”)

- Brainstorm for a few minutes, writing down terms and short phrases that are connected to your current understanding of engineering.
- Draw a concept map based on your brainstorming, placing “Engineering” at the center or top of the drawing and drawing lines to other related concepts.
- After you have sketched in the primary associations, move on to add secondary or tertiary levels of association (or more), if appropriate.

Figure 1. Concept map assignment (example map from [6])
The authors initially, and independently, used the maps for their own sections of the course to create a word cloud for the words added to the concept map by students in that section. The authors then met and discussed the process they used and the challenges they faced when creating the word clouds. They then agreed on a set of heuristics for how to collect the words from the maps:

- If a student used the same word multiple times in different parts of the map (e.g., “design”) the word was repeated on the list the same number of times.
- Common parts of speech (e.g., conjunctions, pronouns, and prepositions) were not included in the lists of words created.
- A noun that was included in student maps in both the singular and plural form (e.g., problem and problems) was captured in the list of words as either singular or plural but not both.
- A common phrase (e.g., “event tree”) was included in the list as a single item by the use of hyphenation (e.g., “event-tree”).

The authors then used the maps from a section of the course taught by another instructor and each author independently created a word cloud for that section. The authors compared their results and agreed that minor differences in applying the heuristics listed above (e.g., the choice of whether to show all nouns as plural) did not significantly impact the resulting word cloud.

After this work to develop a consistent approach to creating the lists of added words on the student concept maps, the authors then created word clouds for each of the sections participating in the project. The resulting word clouds were then shared among the faculty members teaching the course and were used as the basis for two meetings held to discuss the results.

**Results**

On average, the faculty members teaching the modules spent approximately 40 minutes of class time on the concept map activity (including both the pre-and post-activities). Once the heuristics were established for creating the list of words from the final concept maps and the authors had normed their approach to create lists from the maps, creating the word cloud required approximately 15-20 minutes per module. Figures 2 through 9 are the word clouds for each module; Figure 10 is a word cloud created by combining the lists from all of the modules.

In looking at the word clouds, individual faculty members reflected on module-specific outcomes as well as course-level outcomes and noted both some expected and unexpected results. The following sections discuss instructor reflections regarding student learning based on the results from their own module, modules taught by faculty within the same engineering discipline, and across all modules evaluated in the course.

Individual instructors were prompted by this exercise to think about what the word clouds reflect in comparison to what the instructor wanted the students take away from the course. They considered the results both with respect to specific topics that were covered in each module and with respect to the overall goals of the course and the students’ general understanding of
Figure 2. Powering the World: Engineering Design and Energy (Instructor 1). “Design” appeared 5 times.

Figure 3. Powering the World: Engineering Design and Energy (Instructor 2). “Process” appeared 5 times.
Figure 4. Blazing a Path to Design (Instructor 3). “Design” appeared 11 times.

Figure 5. Designing the Sustainable City (Instructor 4). “Design” appeared 10 times.
Figure 6. Engineering Failures: Lessons for the Future (Instructor 5). “Communication” and “Risk” appeared 10 times each.

Figure 7. Design Thinking (Instructor 6). “Design” appeared 13 times.
Figure 8. Design Thinking (Instructor 7). “Design” appeared 5 times.

Figure 9. Design Thinking (Instructor 7). “Functional-decomposition” appeared 4 times.
engineering and engineering ways of thinking. So, for example, do I want the word clouds for my course to have a fairly small number of words in large font, or do I want a variety of words in smaller fonts? Do I want students to leave with common vocabulary and concepts, or do I want them to reflect the variety of possibilities engineering provides? It may seem that the former would make more sense. However, given that this course aims to inspire students to continue with their own passions in engineering, which may or may not relate closely to the module-specific outcomes, it is not necessarily so clear.

Instructors noted that they could easily identify particular “buzz words” used in their modules, which led to a discussion of student motivation. Even though the concept maps are not graded, there is a possibility that students are constructing their concept maps based on what they think the instructor would hope to see. Given the themes of the modules, some of these words became prominent in the word clouds – particularly because they may have been new to the students. Faculty members noted that it is helpful to see what the students are actually hearing – or what they believe the professors want them to hear – because it may not be exactly what they had hoped. One faculty member noted “I learned what I don’t want to teach again.” Instructors also found it useful to note which words were not appearing in the words clouds that might have been expected.

Reviewing the word clouds allows the instructors to re-examine the module learning outcomes. Often we have implicit outcomes that we are looking for that are not stated – looking at these word clouds inspired some faculty members to re-visit the learning outcomes in light of those realizations. For example, one instructor noted that she was explicitly trying to not make her module discipline specific, and that is to some extent reflected in the word cloud, but not quite to the extent she had imagined.
Individual instructors also were able to reflect on how their module is different from and similar to other modules. Faculty members within the same discipline began talking to one another about the word clouds even before the scheduled meetings (all of the word clouds were distributed to all participating faculty members). Some of the word clouds have many words, while other have relatively few. What, if anything, does this tell an individual instructor about what students are taking away from that particular module? The instructors also noticed that some word clouds featured more prominently words related to the overall course outcomes while others reflected more closely the stated module outcomes.

The word cloud for all modules in the course combined shows that, on the whole, students are developing the vocabulary and associated concepts we would hope for based on the common learning outcomes for the course. For example, the word “design” is most prominent, occurring 60 times. Across modules and given the overall learning outcomes for the course, we would have hoped that this would be the case. Similarly, the words “process” and “problems” are common across modules.

Discussion

Overall, the faculty members who participated in this study found the exercise to be helpful and worth the faculty and student time invested. Evidence of the desire for, and potential value of, this type of exercise and resulting conversations comes from the engaged conversations among the participating faculty about how they might modify the exercise and/or how we could modify the analysis in the future to provide additional information. In addition, having the students construct initial concept maps is a useful way to establish a baseline for student knowledge and understanding. Students arrive on campus with widely varying backgrounds (although not as much as at some other institutions) and if an instructor assigns this task and reviews it after the first class, it allows the instructor to identify gaps, misconceptions, and variation in student initial understanding and adjust the tentative course plan to better meet students where they are.

One thing to recognize about the way the authors constructed the experiment is that only words that were added to the students’ concept maps are included in the word clouds. So, for example, if a student included the word “design” in his or her original concept map, it would not appear in the word cloud. The word cloud only indicated changes in the students’ concept maps. By only including words that are added, this approach does not capture or provide any summary of the students’ prior knowledge regarding engineering. It was also noted that some students might have difficulty adding to a concept map that they created at the beginning of the module if their understanding had changed substantially by the end of the module. That is, some students might, if given the opportunity, have preferred to create a new map entirely and have been discouraged at trying to figure out how to modify their original maps.

The participating faculty discussed benefits and drawbacks to using the word clouds as the analysis method. On the one hand, creating the word clouds is a relatively quick and easy way to compile a list of the terms and concepts that students recall at the end of the module. On the other hand, this method does not capture any connections between or relationships among the concepts. Given that this information is available in the concept maps, albeit at varying levels of sophistication, an alternative analysis method could provide a richer picture of student
understanding. For example, having students use a software program to create their maps could facilitate a more in-depth analysis of the students’ concept maps. However, the time required for faculty members to learn and use a program to create the maps is likely to significantly increase the amount of time required for this exercise. Given that the modules are only seven weeks long, this additional time may be an unacceptable cost.

Faculty members participating in the exercise also noted that the sample size associated with each word in a cloud is generally quite small. Even the most prominent words for a single module appear only a few times. Establishing a list of terms – a glossary of sorts – that defines synonyms and groups words together may be might be a useful modification to the approach, especially if it a more extensive quantitative analysis is desired.

Another line of faculty discussion centered on the prompt provided to students. If the goal of the exercise is to encourage discussion among the faculty members teaching the course, then the open-ended prompt is probably appropriate because a more specific prompt would not apply across sections. However, if a faculty member wanted to use this approach to gain a better awareness of student learning in his or her module only, a more focused prompt might elicit more focused student responses.

It also was noted that how the faculty members presented this exercise to their students, both initially and at the end of the module, is likely to have an impact on how students complete the exercise. This is true both in terms of which parts of the instructions are emphasized (or not) and the level of enthusiasm of the instructor in encouraging students to engage with the exercise.

Faculty members were eager to talk about how we might further engage students in this exercise. For example, we discussed the potential benefits of showing word clouds to students based on the initial and/or final concept maps. Several faculty members hypothesized that sharing the initial and final results with the students in a module could also be a useful teaching tool as a way to initiate an evidence-based conversation about the expected outcomes and any differences in student and instructor perceptions.

Finally, the instructors teaching the course agreed that introducing instructors who are new to teaching the course to the word clouds from previous offerings would be a good way to familiarize someone with the course. The overall word cloud does reflect the course-wide priorities, and it allows a new instructor to see at a glance the common themes as well as some of the less common take-aways; it shows both the importance of commonality and the space for difference.

Conclusions

In this study, faculty members teaching sections of an introduction to engineering course used concept maps and word clouds as a way to capture information about student learning within and across sections of the course. Using this approach, individual faculty members were able to gain useful information about student learning in their own course sections, in sections taught by other faculty members in their engineering discipline, and across all sections of the course that participated in the exercise.
A potentially useful modification to the approach might be to ask participating faculty before they start the course to articulate what they would like their students’ word clouds to look like, and then ask them to revisit those ideas when they look at the word clouds that did result from the course. This exercise allows an individual instructor to ask the question “What do I want my word cloud to look like and how will I change my module/section?” It invites instructors to revisit how they have thought about the course.

This exercise also allows, at the course level, for a Department Head or Dean to ask “What do we as a department/college want this word cloud to look like, and what changes should we make at the course level to change the outcomes?”

The exercise requires relatively small amounts of time and promotes individual and institutional reflection about student learning in a multi-section course.

**Acknowledgements**
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**References**


APPENDIX A: Module Descriptions

Powering the World: Engineering Design & Energy (Chemical and Biomolecular Engineering – 2 sections with different outcomes – Instructors 1 and 2)
With the rapid urbanization and growth of developing nations, the energy demands for our world are increasing at a rapid pace. Because of both environmental and practical concerns, the world’s energy portfolio is becoming far more diversified, incorporating renewable and non-traditional energy sources with more common sources such as petroleum and coal. The process by which algae in a pond, the energy of the sun and crude oil in an undersea reservoir are converted into the fuels that keep the world running involves multiple pieces of equipment (known as unit operations), requiring knowledge of a plethora of engineering principles. The organization of these unit operations in an efficient manner that is environmentally friendly and ethically sound is an important example of process design. This section will analyze process design within the context of the energy industry. The backbone engineering principles used in such processes as refineries will be discussed along with the guiding principles used in designing multi-operation processes. This concept of process design in energy will be complemented by a sequential laboratory experiment where biodiesel will be produced and processed.

Blazing a Path to Design (Civil and Environmental Engineering – Instructor 3)
Real world problems do not come with instructions or a solutions manual. As engineers, we train ourselves to define, understand, and solve problems using a process. Within this process, it is important that we engage project stakeholders to appropriately prioritize outcomes and decide on a set of qualitative and quantitative indicators that determine whether the implemented solution is initially successful and continues to perform well over time. In this module, students will complete a preliminary design of a trail system on the main campus of Lafayette College. The goals of the trails are to create new pedestrian routes to several locations within campus and Easton, access potential outdoor learning spaces, and provide additional opportunities for recreation. Students will use fieldwork, interviews, and published resources to develop a preliminary layout of the trails, identify locations that will require grading and/or management of stormwater runoff, and conceptually design trail features and structures. This process will be iterative as students synthesize information to navigate the constraints, risks, and uncertainties associated with the project.

Designing the Sustainable City (Civil and Environmental Engineering – Instructor 4)
When we look at a city, most of what we see (and much of what we don’t) was designed by engineers. These buildings, bridges, roads, dams, water and wastewater systems, and parks, collectively termed “infrastructure,” help to determine urban quality of life. Much of our infrastructure was designed and constructed 50 years ago or more. Good infrastructure design takes into account the needs of many different groups of people, as well as the environment. This module introduces “design thinking” as a way of approaching the design process and asks how we design to 1) preserve and rejuvenate this existing infrastructure, and 2) create new infrastructure that will help to make our cities more sustainable. Students will use [the local city] as a laboratory to apply principles of reverse engineering to understand existing infrastructure and apply the design process to develop creative solutions to urban infrastructure problems.
Engineering Failures: Lessons for the Future (Civil and Environmental Engineering – Instructor 5)

Unless they are constructed and used entirely at sea, in the air, or in space, all structures are supported by soil and/or rock for at least part of their design life. Geotechnical engineering is the area of engineering that focuses on the use of soil and/or rock as a part of engineering design. Geotechnical engineering has often been called more of an art than a science because the materials involved are not manufactured to given specifications (such as the specifications associated with steel and concrete design) but are the natural soils and rocks present at the location where a client wants to develop a project. Because of the uncertainties associated with using natural materials, geotechnical engineering practice has developed, in part, due to lessons learned from failures. In this module, students will learn about some well-known geotechnical failures and about how those failures were used to improve future designs. Students in the module will also document the current conditions of a structure and assess whether the structure may be at risk of failure.

Design Thinking (Mechanical Engineering – Instructor 6)

Engineers design technologies - products, processes, experiences - to enhance the human experience. This module is an immersive introduction to the engineering design process, from identifying needs and desires of a population to brainstorming, detailing, and iterating design solutions. What social and political factors drive engineering innovation? Who decides what technologies matter? What is a “good” solution, and for whom is it “good”? The principles we will discuss apply across disciplines and applications, and we will explore their relevance in different fields of engineering. Students will have team-based, hands-on design experiences with several creative projects to develop an understanding and practice of engineering design. In two major projects, students will reverse-engineer an existing everyday device of their choosing, and design their own novel assistive technologies. Through these projects, students will reflect on the ethics and societal considerations in the practice of engineering design, and leave with a more nuanced understanding of the ways technology and humanity interact. What does it mean to enhance the human experience, and how do we achieve that?

Design Thinking (Mechanical Engineering – 2 sections – Instructor 7)

Design is the art and science of innovation: creative problem solving to meet the needs of individuals and societies. Design thinking applies to innovation across the built environment, including the design of products, services, interactive technology, environments, and experiences. Our focus is on user-oriented, collaborative approaches to design. In order to develop solutions integrating user and functional perspectives, we emphasize the importance of process and the development of strategies. Students will reverse engineer common devices and systems, and complete hands-on design projects. Students work collaboratively in a studio environment to create a shared understanding of the people they design for (and with) and the product ideas they develop. By applying this design process to several creative projects, students will develop communication skills, learn strategies for optimizing team dynamics, and refine an iterative design process, weighing objectives, testing prototypes, and using feedback to revise goals, objectives, and even the problem statement.