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Fostering Professional Practice Skills in a Redesigned Materials Science Course for Engineering Students

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Abstract

There has been an increasing demand for engineering education to include more opportunities in the curriculum for students to develop the professional practice skills necessary for the modern, global workforce. Many engineering programs have included non-technical skills in freshman introduction to engineering courses and design courses such as the capstone design course in the senior year. However, there is a decreased emphasis on these important skills in the middle two years of a typical engineering curriculum, and there is an opportunity to find a place for these skills to be developed in the context of an engineering science course. In an effort to incorporate more professional skills during the middle years, a Materials Science course for Mechanical Engineering majors was redesigned to include specific learning goals that address creativity, teamwork, communication, lifelong learning, environmental impact, and societal impact. The course has for many years been taught using a traditional, lecture based approach, and the new format adopts a student-centered, active learning approach with an emphasis on project-based learning and integrative learning. While including more focus on professional skills, it was also important to ensure sufficient learning of the body of knowledge in materials science necessary for practical application in the Mechanical Engineering profession. An effort was made to align the learning goals with learning activities, assessments, and products. The course changes were also intended to increase student engagement by developing students' intrinsic motivation with a learning environment that promoted competence, relatedness (community and purpose), and autonomy. This paper describes representative activities including projects, in-class activities, homework assignments, and tests. The methods of assessing student work are also discussed. Qualitative student feedback is reported based primarily on student surveys.

Introduction and Motivation

There have been numerous reports, studies, and books that call for engineering education to not only educate for technical competence but to also educate for the professional practice skills necessary for the modern, global workforce.[1,2,3,4] Engineering programs have responded to this call for change by introducing non-technical skills in freshman introductory engineering courses, however the professional practice skills are mainly being included in design experiences such as the capstone design course in the senior year. The middle two years of a typical engineering curriculum are crowded mostly with engineering science courses and laboratory based courses. It can be challenging to incorporate professional skills into engineering laboratory and engineering science courses while maintaining sufficient technical content, but it can be done.[5,6] This paper presents the author's attempt to include professional practice skills in the context of a Materials Science course.

The main goal of this effort was to redesign an existing Materials Science to include specific learning goals that address creativity, teamwork, communication, lifelong learning, environmental impact, and societal impact. The course had for many years been taught using a traditional, lecture based approach, and the new format adopts a more student-centered, active learning approach with an emphasis on project-based learning and integrative learning.

This paper describes the redesign strategies and the results of the initial offering of the redesigned course that was taught in the fall 2015 semester. Many of the strategies were adapted from the successes that Olin College has seen in their unique curriculum. In particular, the strategies and method used in Olin's Materials Science Course and Stuff of History course, which integrates Materials Science and History, were particularly helpful.[7,8]

Previous Course framework

Materials Science is a junior level required course in the Mechanical Engineering curriculum at Norwich University, a teaching-focused, primarily undergraduate university in the state of Vermont. The course is delivered in a 14 week period and is three credit hours. Course enrollment has ranged from 22 to 36 students over the past five years. The catalog description of the course states:

> An introduction to the science of materials based on the physics and chemistry of their internal structures. The effects of structure on the properties and behavior of metallic, polymeric, ceramic, semiconductor, and composite materials.

The author has taught the course for many years (since 2003) using a traditional lecture style format. The course design was content driven and teacher centered. The course content and sequence followed very closely the chapter sequence in traditional Materials Science textbooks such as those authored by Callister or Shackelford. The course goals were also aligned very closely with the Materials Science content presented in the chapters of the textbook. Most of the course goals involved lower order thinking skills for understanding and remembering the Materials Science content. The course meets for 150 minutes per week either as three separate 50 minute periods or two 75 minute periods.

A typical class period would involve the instructor presenting the material in various ways include Powerpoint presentations, written notes on the board, and working out example problems from the end of chapter problem set. Occasionally students would work on short problems in class that would involve small groups of two or three working together. In a typical week, homework assignments were given that were predominately taken from the end of chapter problem sets and included mostly closed-ended type problems. Students were expected to submit solutions that they worked out individually, although they were encouraged to help each other if they had problems. Short quizzes were given occasionally to help students prepare for one of the three major hour tests given in the semester. The hour tests consisted of a closed book, closed notes, short answer part followed by an open book, longer answer and problem solving part. Typically, one design type project was given at the end of the semester. The final grade in the course breaks down to 55% from the three hour tests, 20% from homework, quizzes, and projects, and 25% from the final exam.

New Course Design and Delivery

In order to maximize student engagement in the redesigned course, a variety of student-centered, active learning strategies were employed with the main learning strategy being project based learning.[9] Project based learning was also chosen to provide a realistic context for incorporating the professional practice skills.[10] The learning environment and experiences were also guided by

Self-Determination Theory where the students are more intrinsically motivated if their learning experiences include competence (mastery and success), relatedness (community and purpose), and autonomy (choice and control).[11] An effort was made to align the learning goals with learning activities, assessments, and products.

Learning Goals

The design of the new course started with the establishment of learning goals that included not only the lower order thinking necessary for understanding the Materials Science technical content, but also specific learning goals necessary for professional practice: design, creativity, teamwork, communication, lifelong learning, information literacy, environmental impact, and societal impact. An emphasis was placed on higher order thinking skills. The course goals are given in Table 1.

Table 1. Course Goals

	Goal description	**Abbreviated name**
1	Relate material composition and processing methods to structure and properties, and in turn to the performance of the major classes of materials (metals, ceramics, polymers, composites).	Structure, processing, properties, performance connections
2	Apply and integrate materials related knowledge from each of the four elements (structure, properties, processing and performance) to solve materials selection and design problems for a range of modern engineering applications.	Materials selection and design
3	Evaluate non-technical, contemporary issues related to environmental and societal impacts of materials and materials systems in a global context.	Environmental and societal context
4	Select and utilize diverse and relevant resources (software tools, textbooks, internet, library resources) to integrate and apply the knowledge and tools necessary for being successful in this course.	Information literacy
5	Work effectively as a member of a team.	Teamwork
6	Use written, oral, and graphical communication to convey methods, results, and conclusions.	Communication
7	Demonstrate a capacity for self-directed, lifelong learning, including goal setting, decision-making, project planning, resource discovery and evaluation, personal development (autonomy, self-motivation, self-confidence, self-reflection).	Lifelong Learning
8	Develop and apply attitudes and skills for creativity within the context of materials science and engineering.	Creativity
9	Develop sufficient understanding of the Body of Knowledge (Technical content) in materials science necessary for practical application in the Mechanical Engineering profession. a. Basic classification, structure, properties, processing, and performance of engineering materials (metals, polymers, ceramics, composites) b. Periodic table of elements, atomic bonding, and crystalline structure. c. Grain structure, crystalline defects and strengthening mechanisms. d. Fundamental principles and mechanisms of diffusion in solids. e. Mechanical behavior of materials including stress-strain curves, elastic and plastic deformation, viscoelastic deformation, and hardness. f. Basic fracture mechanics and the modes of failure including ductile versus brittle failure, fatigue failure, and creep failure. g. Principles of alloying and phase diagrams. h. Heat treatments for modifying the microstructure and properties in ferrous and non-ferrous alloys.	Materials Science Body of Knowledge

Project Work

The projects provide the framework for learning in the course. There were three main projects: Project 1 on Properties, Structure, Performance, and Impacts of Everyday Consumer Products, Project 2 on Materials Analysis and Societal Impact of a Historical Artifact, and Project 3 on Sustainable Design. Most of the project work was team based consisting of three person teams. After project 1, the students formed new teams, and stayed together through project 2 and 3. This format provided for some variability in teams, but also allowed for some consistency and a smooth transition into project 3. Most of the learning activities were designed to support the project work and included a combination of in-class activities and out of class activities.
A summary of each project is presented along with the associated learning activities, products, and assessments.

Project 1: Properties, Structure, Performance, and Impacts of Everyday Consumer Products

The first project involved the students working in teams to explore Materials Science in the context of an everyday consumer product. The students were asked to explore connections among material composition, atomic and molecular structure, and material properties (mostly mechanical and thermal properties). The specific objectives of this project were:

a. Identify the materials used for various components of your team's object;
b. Characterize of the material properties of the object components
c. Identify of the structure or lack of structure in your materials (What atoms, ions, and molecules are there? How are the atoms, ions, or molecules arranged?);
d. Examine of material selection for the design (Why were these materials chosen?),
e. Explore of the environmental impacts of your materials
f. Build connections among composition, structure, properties, and performance.

Project 1 was designed to make progress toward achieving the course goals in the following areas:

Technical area goals: (1. Structure, properties, performance connections; 9. Materials Science Body of Knowledge - Topics a, b, c, and e (details given in Table 1)

Professional skills goals: (3. Environmental and societal context; 4. Information literacy; 5. Teamwork; 6. Communication; 7. Lifelong Learning; 8. Creativity)

Some examples of consumer products that the students chose to work on included a toy Nerf gun, a calculator, a water bottle, a bicycle lock, a flashlight, a mechanical pencil, a cigar caddy, a pocket knife, a fishing lure, and a stapler. The learning activities were designed to actively engage the students in the process of achieving the objectives of the project and to make progress toward achieving the course goals. The assessments of the student's performance on the projects were based on a variety of products including weekly homework assignments, project proposal, project poster, and an individual, take-home test at the end of the project. Figure 1 gives the overview of learning activities, products, and assessments associated with Project 1.

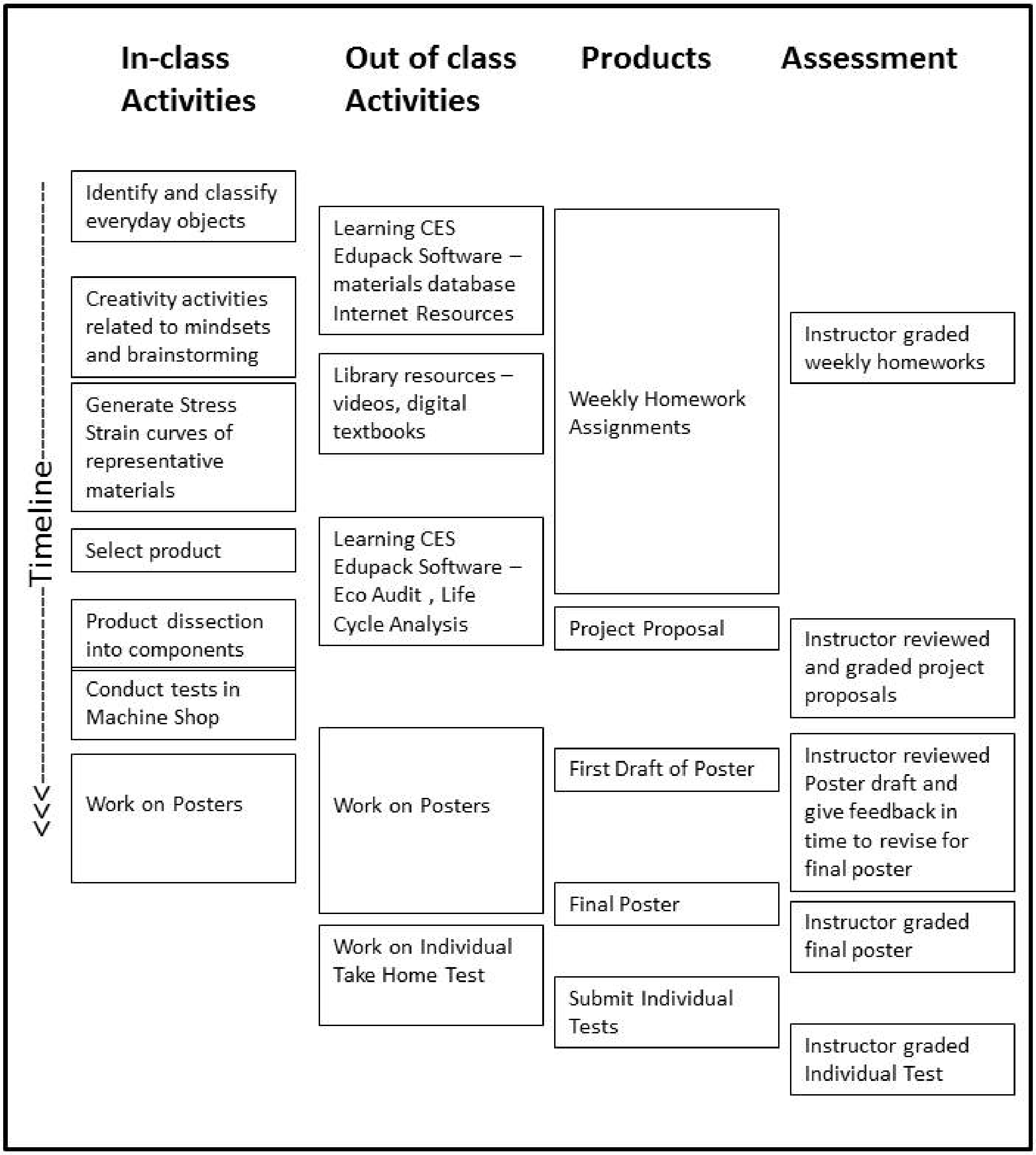

Figure 1. Activities, products, and assessments associated with Project 1

Without a required textbook designated for the course, the ability for the students to seek out and utilize appropriate resources and tools (information literacy) was one of the professional skills emphasized in the course. Project 1 homework assignments guided the students toward relevant resources including the valid resources on the internet, the campus library resources, and the CES EduPack software. CES Edupack includes an extensive materials and process database and provide tools for materials selection and sustainability considerations in design. The software was being used for the first time in this course to evaluate its feasibility for not only Materials Science, but also in other courses in the curriculum.

To give an example of one of the in-class activities that occurred early in the course, the instructor brought a large assortment of small everyday objects into class. The objects were made of a variety of materials including ceramics, polymers, metals, and composites. Each team of three to four students was given the following instructions:

1. Choose from the selection of everyday objects. For example, a nail, or a paper clip, or an eraser.
2. State which of the four main materials classifications the object belongs to: Metals, Polymers, Ceramics, or Composites.
3. What specific material is it made of (be as specific as you can)? For example, steel or aluminum.
4. What material properties are important for the intended function of the part? You don't need to address all of the material properties listed, but rather the ones that you know the meaning of and the properties that are most important for the function of the part. For example, if it needs to be very strong and not break easily, the material's yield strength and tensile strength need to be high.
5. Could the object be made out of a different material? If so, what material would that be and how would it be different than the material it is actually made of.

One of the main project deliverables was a team poster. Each team was required to generate a poster draft that was submitted electronically and quickly reviewed by the instructor who provided constructive feedback. Final posters were then submitted and printed for display in the classroom. Students were allowed to review each other's posters and provide comments on what they like and what could be improved. At the end of the project, individual take home tests were given where questions were given that addressed materials science in the context of the project. A few examples of test questions included:

1. What material did you identify your part to be made of?
    a. What major material classification does your material belong to?
    b. Explain how you identified your material?
    c. What tests or experiments did you perform?

2. Show a schematic of the most likely atomic arrangement of atoms for your material. Show the unit cell if it is a metal or the mer unit if it is a polymer. It will be more meaningful to label some of the elements on your schematic, so you may have to do some graphics editing to do this.

3. Summarize the Environmental Impact analysis that your team did for your part or product.
    a. What questions or interesting angles did you pursue about assessing the environmental impact?
    b. Explain how you used the CES Eco Audit tool.
    c. What assumptions did you have to make?
    d. What results and conclusions did you come up with?
    e. What phase of the product life cycle did you find to be the most harmful to the environment?

Project 2: Materials Analysis and Societal Impact of a Historical Artifact

For the second project the students were asked to select an artifact from the university's Sullivan Museum and History Center to identify and study the materials from which the artifact was made. In addition to characterizing the underlying materials science of the artifact, they researched the historical and cultural significance and identified modern day counterparts and applications of the metal alloys identified in the artifact. The project enabled the students to learn about the microstructure-processing-property connections in metal alloys by examining phase diagrams, thermal and mechanical processing, and strengthening mechanisms in metals within the context of historic and modern applications.

The specific objectives of project 2 were:

a. Identify materials used for components of your artifact, and interpret what these properties mean for performance and impact of the materials.
b. Research and describe important contextual factors related to the history, design, use, and societal impact of your artifact.
c. Identify a modern counterpart of your artifact and substitute modern materials. Compare the materials in your historical artifact to those in your modern counterpart.
d. Identify alternate modern day applications of the materials found in your artifact.
e. Explore materials science relationships among structure, processing, properties, and performance.
    - Use of phase diagrams to analyze and predict microstructure and properties.
    - Explanation and prediction of microstructural and property changes that result from compositional modification, and mechanical and thermal processing.
    - Use of processing techniques to achieve particular microstructures or a specific set of properties in metallic materials.
f. Hone your collaboration skills and positive teaming interactions.

Project 2 was designed to make progress toward achieving the course goals in the following areas:

> Technical area goals: (1. Structure, Processing, properties, performance connections; 9. Materials Science Body of Knowledge - Topics b, c, d, e, g, h (details given in Table 1)
>
> Professional skills goals: (3. Societal context; 4. Information literacy; 5. Teamwork; 6. Communication; 7. Lifelong Learning)

Some examples of the museum artifacts that the students chose to work on included a Luger pistol, a U.S. Army Bolo knife, a Captain's sword, a trumpet, a submachine gun, a soldier's helmet, and a ship's bell. The assessments of the student's performance on the projects were based on a variety of products including weekly homework assignments, project proposal, project poster, a short team report, and an individual, take-home test at the end of the project.

One of the main project deliverables was a museum display poster. The posters were designed to be displayed in an exhibit in the Sullivan Museum, and all of the posters along with the artifact that the team worked on are on display in the museum as shown in Figure 2.

Figure 2. Example of poster products from Project 2 on display in the university's Sullivan Museum.

Project 3: Sustainable Design

For the final project, the students were asked to apply materials science and materials selection in a product redesign scenario. Teams selected an existing product and identify different features of the product that could be redesigned with sustainability as the primary consideration for the redesign. They also examined materials science connections related to their product. This final project allowed for the most flexibility and choice with the fewest constraints. Students were asked to develop their own specific goals within the following framework:

1. Redesign your product for sustainability (team effort): Focus on two different ways in which your product can be improved from a sustainable design perspective.
   a. One redesign must be a material substitution of a component of the product.
   b. The second design modification is your choice.

2. Make Materials Science connections (Individual effort supported by your team)

3. Establish Personal Goals (Individual effort)

Project 3 was designed to make progress toward achieving course goals in the following areas:

> Technical area goals: (1. Structure, Processing, properties, performance connections; 9. Materials Science Body of Knowledge - Each team member was allowed the choice of focusing on two topics form the list: b, c, d, e, f, g, and h (details given in Table 1)
>
> Professional skills goals: (2. Materials Selection and Design; 3. Environmental context; 4. Information literacy; 5. Teamwork; 6. Communication; 7. Lifelong Learning; 8. Creativity)

Some examples of the products that the students chose to work on included a skateboard, a classroom chair, a phone case, a box fan, a snow shovel, a toothbrush, a backpack, and a snow sled. The assessments of the student's performance on the projects were based on a variety of products including weekly homework assignments, project proposal, an individual report, and a team oral presentation given during the final exam period. Two examples of slides from those final presentations are shown in Figures 3 and 4.

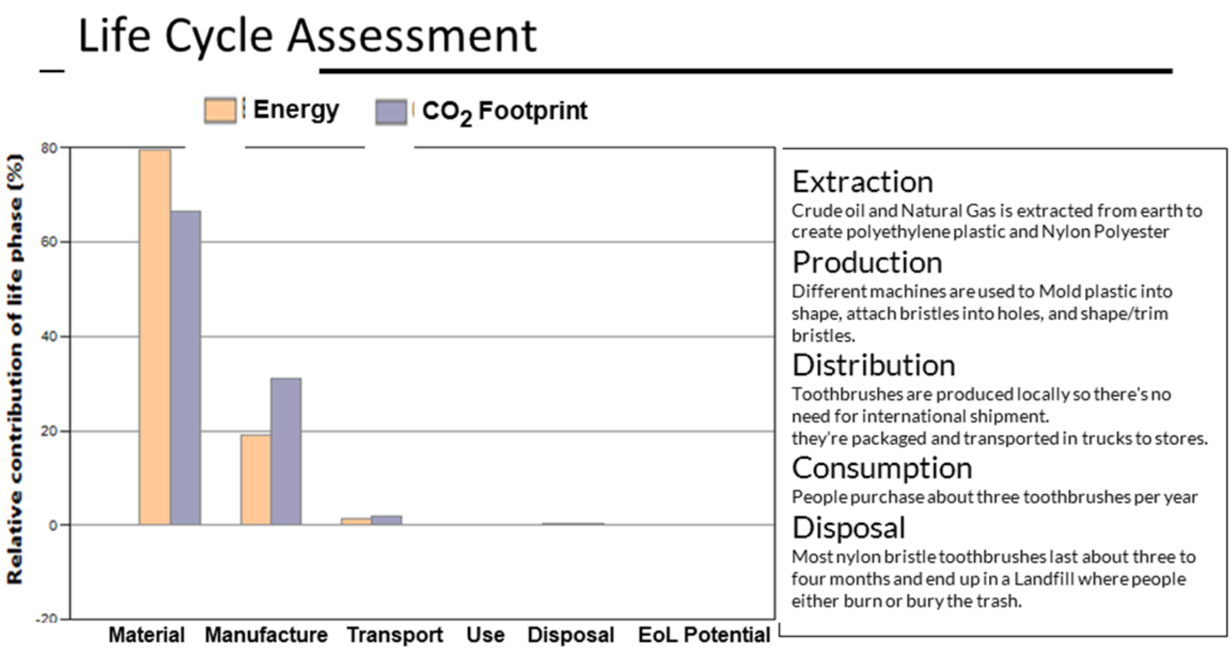

Figure 3. Example of project 3 final presentation slide - life cycle assessment of a toothbrush.

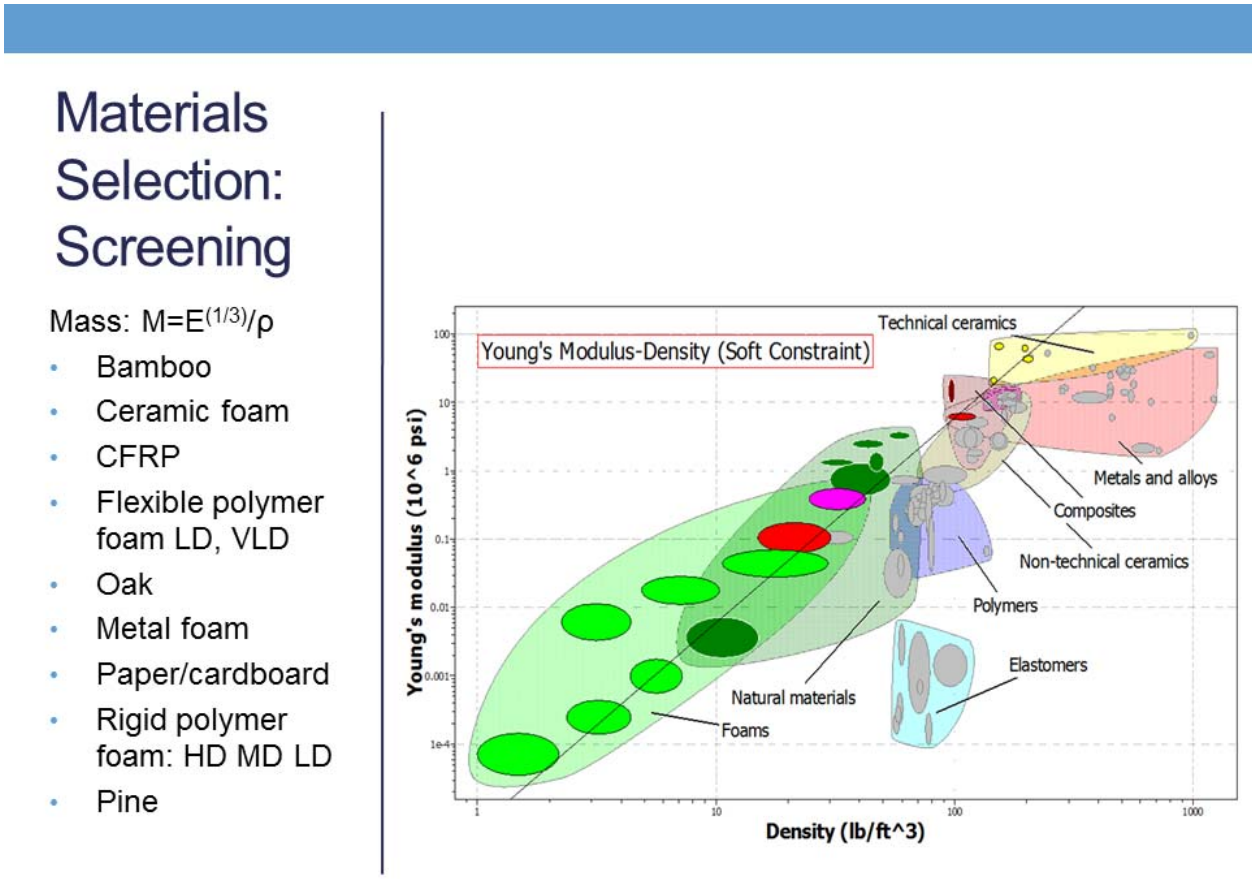

Figure 4. Example of project 3 final presentation slide – material selection for foot deodorizers.

Evaluation Results

After the completion of the course students were asked to complete a survey. A total of 32 students were in the class, and 22 students responded to the survey. One part of the survey asked the students to evaluate the achievement of the course objectives using a Likert scale.
The question asked:

> Please indicate the degree to which you agree/disagree that you have acquired the abilities/skills addressed in the course goals. Answer questions 1 through 9 using the following scale: 1: strongly disagree, 2: disagree, 3: neutral, 4: agree, 5: strongly agree

The results of the survey are shown in Table 2. The number of respondents in each category of the Likert scale is reported along with the corresponding percentages. The final column represents the total number of respondents in the Agree and Strongly Agree categories.
The percentage of students that felt like they achieved the goals (sum of agreed and strongly agreed categories) ranged from 68.2% to 86.4% with Environment and Societal context being the lowest and Communication the highest.

Table 2. Student Evaluation of Course Objectives

Course Goal	n	SD	D	N	A	SA	A + SA
1. Structure, processing, properties, performance connections	22	0 (0%)	0 (0%)	3 (13.6%)	13 (59.1%)	6 (27.3%)	19 (86.4%)
2. Materials selection and design	22	0 (0%)	1 (4.5%)	4 (18.2%)	10 (45.5%)	7 (31.8%)	17 (77.3%)
3. Environmental and societal context	22	0 (0%)	1 (4.5%)	6 (27.3%)	8 (36.4%)	7 (31.8%)	15 (68.2%)
4. Information literacy	22	0 (0%)	2 (9.1%)	3 (13.6%)	9 (40.9%)	8 (36.4%)	17 (77.3%)
5.Teamwork	22	0 (0%)	0 (0%)	5 (22.7%)	7 (31.8%)	10 (45.5%)	17 (77.3%)
6. Communication	22	0 (0%)	0 (0%)	3 (13.6%)	9 (40.9%)	10 (45.5%)	19 (86.4%)
7. Lifelong Learning	22	0 (0%)	1 (4.5%)	5 (22.7%)	9 (40.9%)	7 (31.9%)	16 (72.7%)
8. Creativity	22	0 (0%)	0 (0%)	6 (27.3%)	10 (45.5%)	6 (27.3%)	16 (72.7%)
9. Materials Science Body of Knowledge	22	0 (0%)	1 (4.5%)	4 (18.2%)	12 (54.5%)	5 (22.7%)	17 (77.3%)

Students were also asked to respond to questions related to professional skills emphasized in the course. Using the same Likert scale used to evaluate course goals, the students were asked the following question related to creative, and the results are given in Table 3:

> The idea generation and brainstorming methods learned in the course helped me generate more creative solutions in the projects.

Table 3. Student Evaluation of Creativity on Project Work

Question	n	SD	D	N	A	SA	A + SA
The idea generation and brainstorming methods learned in the course helped me generate more creative solutions in the projects.	22	1 (4.6%)	0 (0%)	4 (18.2%)	13 (59.1%)	4 (18.2%)	17 (77.3%)

To allow for more elaboration on creativity, the students were asked the following open ended question:

> Describe the different aspects of the course that allowed you to be more creative in your project work.

A selection of student responses to the open ended creativity question included:

> *The ability to choose individual objects on projects allowed for a lot of creativity as did the warm up methods we learned.*
>
> *I was able to think outside the box by using resources and peer to peer ideas.*
>
> *The brainstorming ways*
>
> *Group Projects that involved going to the machine shop as well as having a wide variety of choices for different items to use in projects.*
>
> *The CES edupack really was integral into my ability to be creative because of the vast amount of information that was available through the software it allows you to make many different and significant material substitutions because you have so many at your fingertips that you wouldn't have considered right off the bat.*

The ability to choose the specific objects for the projects was mentioned by five students as being the aspect of the course that allowed for the most creativity.

To address information literacy, the students were asked how often they used different resources throughout the course using the following Likert scale: 1: Never, 2: Very Rarely, 3: Rarely, 4: Occasionally, 5: Frequently, 6: Very Frequently. The results are shown in Table 4.

Table 4. Student Evaluation of Use of Resources

Question: How often did you use each of the listed resources throughout the course	**n**	**Never**	**Very Rarely**	**Rarely**	**Occasionally**	**Frequently**	**Very Frequently**
CES EduPack Software	22	0 (0%)	0 (0%)	2 (9.1%)	3 (13.6%)	8 (36.4%)	9 (40.9%)
Library Resources (databases, videos, digital textbooks, etc.)	22	1 (4.5%)	1 (4.5%)	9 (40.9%)	5 (22.7%)	5 (22.7%)	1 (4.5%)
Materials provided by Instructor (files posted on NUoodle course page)	22	0 (0%)	0 (0%)	2 (9.1%)	2 (9.1%)	13 (59.1%)	5 (22.7%)
Internet Resources that you found on your own	22	0 (0%)	2 (9.1%)	2 (9.1%)	4 (18.2%)	4 (18.2%)	10 (45.5%)

The two resources that were utilized most frequently were CES EduPack software and the Internet. The instructor provided resources were utilized frequently, and the Library resources were utilized less frequently.

One open ended question was asked about Information Literacy:

> Comment on how the project work supported your learning of both the technical content as well as relevant non-technical considerations.

Student responses to this question included:

> *I was able to take away a host of non technical learning as outlined in the syllabus*
>
> *The project work, I feel, made it necessary to completely understand the class material.*
>
> *Unless the class material was understood, it was difficult to do well on the projects.*
>
> *The projects required us to consider the technical reasons behind the specific materials shown for the given object or artifact. They also required us to consider the historical context of the material and how those materials relate to society at that given time period.*
>
> *Project work definitely helped in our independent work to find information, use relevant information and present it in a desirable way.*
>
> *It helped a lot because when I had a question or some trouble I could turn to my group mates for help and I found group learning very effective.*
>
> *The projects, particularly the artifact one, allowed us actual real world application, which was greatly appreciated.*
> *We had to use what we learned in class as well as do our own research if we came upon something we were not familiar with.*

Additional questions were asked about what the students liked and disliked about the course. For the question about what they like most about the course, the following responses were given.

> *I liked the relaxed class atmosphere. I feel that allowed for an easier time in learning the material.*
>
> *The grading consisted mainly of creative projects that required us to apply material science knowledge gained in class.*
>
> *I like the individual work a lot in groups.*
>
> *I liked doing posters as assessments instead of simple reports or presentations. It changed things up a bit.*
>
> *The Artifact assignment*
>
> *Material was interesting as well as grading was very fair*

I liked the history project that we did in conjunction with the library because I got to study in depth what made the Thompson work and what it was made of.

I liked the fact that we worked in groups.

Based on the student responses, the project work was well received and provided the teamwork and real world relevance to studying the material in an interesting way. Project 2 on the historical artifact study seemed to be the project that was most interesting and engaging to the students. For the question on what they liked least about the course, the following responses were given.

Working with some classmates that contributed very little.

sometimes going into too much detail

Idea generation

I feel that the second and third projects may have been too close together.

The different class style took me for a loop.

There was too much material presented at once in some of powerpoint slides/handouts and sometimes it was difficult to decipher and use the examples provided.

The final project because I had a foggy idea of what exactly was expected of it. I thought that we were actually redesigning the object to make it.

Summary and Future Work

This paper summarizes the initial effort and results of the transformation of a Materials Science course from a traditional teacher centered, lecture based course driven by technical content to a student centered, project based course with an emphasis on professional skills. The learning strategies were intended to maximize student engagement and interest in the course material. The pilot offering of the redesigned course was discussed, and the initial feedback from students was very positive. The course will be offered again in the fall of 2016, and the author will continue to teach the course using the redesigned format. One area that will need to be studied more closely is the influence that the new course format has on student motivation and how effective the course is for promoting student competence, relatedness, and autonomy. The use of The Situational Intrinsic Motivation Scale (SIMS) to measure motivation was attempted during the final project, but the response rate was low (below 50% of the class), and it was only measured once.[12] The plan for the next offering of the course is to measure motivation more frequently throughout the course and to attempt to get a better response rate. Another future study that is planned will provide direct measures of the student’s professional skills to determine the effectiveness of the new course format in acquiring those skills.

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