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Designing a Sophomore Materials Science Laboratory Course Centered on Sustainability

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Design of a Sophomore Materials Sciences Laboratory Centered on Sustainable Design.

This paper discusses the design and creation of a sophomore materials science laboratory at the University of Florida (UF) centered on Sustainable Materials and Design. The curriculum committee for the department examined course progression and determined a need for a sophomore laboratory aligned with the Introduction to Materials Science and Engineering course. This paper looks at how the laboratory curriculum was developed by the author to meet departmental needs, as well as a design for student learning through inclusion of research based best practices aligned with ABET criteria. The course explores the materials tetrahedron for metal, ceramics, polymers, composites, centered on the theme of sustainability and engineering design, matched to engineering challenges for societal benefit. The course uses case studies, Granta CES software, laboratory and design activities, with selected readings to provide relevance for core concepts in materials science early in student's academic career. The goal of this paper is to provide a model of how other universities can design laboratories for students, aligning best practices with departmental goals.

Background

A 2008 report from the *Workshop on Materials Science and Materials Engineering Education* sponsored by the National Science Foundation September 18-19, 2008, promoted changes for undergraduate programs in materials science[1]:

> "To attract more students to the discipline, materials programs should change the message used to engage prospective undergraduates. The discipline is an enabling one and one that has the potential to provide technological solutions to critical societal issues. This type of message needs to be used to excite students about opportunities in the field."

Materials Science has a long history paralleling the development of civilization[2]. In early stages of human civilization, natural materials were developed into tools for survival. With the advent of metallic ages, humans utilized materials to make tools and ornaments that advanced living conditions and allowed for advancement of knowledge. Critical to human advancement was the ability of early people to select a material based on considerations of properties needed, availability, workability and performance in application. Early human advancement was tied to the ability of humans to understand the materials tetrahedron and apply it to find new materials having desirable properties for some application.

Despite this call from NSF, and the aligned history of human civilization and materials, there are few university MSE departments[3] that offer students coursework that combine societal aspects and engineering concepts in a laboratory setting. Engineering is a professional practice that exists to solve societal problems, and having an understanding of how materials sciences is woven into technological advancements to solve human problems is essential to development of a well- rounded engineer, and aligned to the ABET Criteria, especially for *c* & *h-j* for design, contemporary issues, and social context.

Laboratories are a natural fit for coursework combining development of engineering practices and skills aligned with core content theories. Research indicates engineers "learn by doing"[3-7], and that laboratory experiences are critical to development of professional engineers. While there are variations in objectives for laboratory in the research literature, an approach taken by Ma and Nickerson[7], who conducted a literature review on laboratory objectives and then aligned them to ABET objectives will be used here as a frame for discussion. It is easy using this frame to connect and extend the original work[7] to ABET goals for 2015 as shown in Table 1. This revised frame was used by the author in the development of the sophomore laboratory at the University of Florida.

Laboratory Goals	ABET Goals (2006)	ABET Goals 2015
Conceptual understanding	Illustrate concepts and principles	(a) an ability to apply knowledge of mathematics, science, and engineering (e) an ability to identify, formulate, and solve engineering problems (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.
Design Skills	Ability to design and investigate Understand the nature of science (scientific mind)	(b) an ability to design and conduct experiments, as well as to analyze and interpret data (c)an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
Social Skills	Social skills and other productive team behaviors (communication, team interaction and problem solving, leadership)	(d) an ability to function on multidisciplinary teams g) an ability to communicate effectively
Professional Skills	Technical/procedural skills Introduce students to the world of scientists and engineers in practice Application of knowledge to practice	(f) an understanding of professional and ethical responsibility (h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context

		(i) a recognition of the need for, and an ability to engage in life-long learning (j) a knowledge of contemporary issues

Table 1: Updated Laboratory Goals[7] re-aligned to ABET 2015.

Sustainable Teaching and Materials Science Programs

Most materials scientists and engineers would agree that materials are central to creating a sustainable environment. Many universities are starting certificate programs in sustainability with coursework sprinkled across departments, including MSE departments. While several materials sciences departments offer coursework for students aligned with principles of sustainability, few offer laboratory programs aligned with sustainability. A 2012 paper in the *MRS Bulletin* by Lesar, Chen and Apelian describe how sustainability was woven into coursework at Iowa State, California Polytechnic, and Worcester Polytechnic[8]. While all three universities provided curriculum infusing concepts of sustainable development and the role of materials in a sustainable environment, only California Polytechnic linked it with a project based learning opportunity for students in their freshman year[8]. In many courses using a theme of sustainability, emphasis is placed on learning and using green design principles, methods, tools and materials. Example activities include life cycle assessment, eco-efficiency and eco-effectiveness. Generally a systems perspective is employed to focus on material and energy flows over a complete product life cycle.

At University of Florida students may major or minor in sustainability studies, and courses can receive a certification of alignment from the Office of Sustainability if their syllabus meets standards set by the department of sustainability studies. This includes incorporation of sustainability practices, including ethics and design. Once a course receives this designation, students within the home department can use this course towards their minor in sustainability. As part of this process, the author attended a week long workshop offered by the Office of Sustainability which provided cross disciplinary faculty with the resources and interdisciplinary interactions to begin incorporating sustainability into their courses. Currently, the only sustainability courses offered at within the College of Engineering are within Engineering School of Sustainable Infrastructure and the Environment, entitled “Green Engineering and Design for Sustainability” it is a 4000 level course for upperclassmen.

Sophomore Laboratories

Many MSE departments offer laboratories at the sophomore level including MIT, Clemson, Cornell, Rochester and University of Arizona. These laboratories are designed to give students hands-on experience with concepts developed in the lecture course, generally the “Introduction to Materials Science and Engineering”. A survey of university department syllabi found the majority of sophomore laboratories at these universities to be focused on a few techniques and tools, mainly related to mechanical behavior of materials. In the survey undertaken, no university material science departments were found to offer a course related to sustainable materials.

Within the MSE Department at UF, laboratories are central to the MSE student experience. As part of an ongoing redesign of curriculum within the department, in 2013 the Junior Laboratory courses were redesigned to support the core content courses that all MSE students take in their junior year. Additionally, the laboratory coursework was designed to highlight the Structure-processing-properties relationships and characterization aspects of materials engineering. In the senior year, students take specialty labs based on their area of interest. Currently the department offers senior laboratories in Polymer Processing, Metal Processing, Ceramic Processing and Electronic Device Processing. The senior experience for laboratories is focused on the processing, optimization and design aspects of materials sciences.

As part of the redesign of the laboratories, courses that were "bundled" with laboratory components (i.e. a four credit polymer processing class plus lab) were unbundled by the curriculum committee to produce a stand-alone 3 hour lecture course, and a 1 hour student laboratory. By doing this, an additional credit hour was found to be available for a new course. Below is a snapshot of how the sophomore laboratory will fit into a student's schedule. The one credit laboratory class will be a two hour meeting once a week. It is anticipated there will be 50-60 students in the course, and sections will be fifteen students or less each, allowing for cooperative groupings of students.

Semester 3	Credits
EIN 4354 Engineering Economy (3) or MAN 3025 Principles of Management (4) or MAR 3023 Principles of Marketing (4)	3-4
EMA 3010 Materials	**3**
MAC 2313 Analytic Geometry and Calculus 3 (GE-M)	**4**
PHY 2048 Physics with Calculus 1 (State Core GE-P)	**3**
PHY 2048L Physics with Calculus 1 Laboratory (GE-P)	1
Computer programming course (COP 2271 or see advisor for approved list)	2
Total	16-17

Semester 4	Credits
EGM 2511 Engineering Mechanics: Statics	3
EMA 3000L Sophomore Materials Lab	1
EMA 3011 Fundamental Principles of Materials	3
EMA 3800 Error Analyses and Optimization Methodologies in Materials Research	3
MAP 2302 Elementary Differential Equations	**3**
PHY 2049 Physics with Calculus 2	**3**
PHY 2049L Physics with Calculus 2 Laboratory	1
Total	17

Figure 2: Student Catalog for 2016 MSE students for sophomore year at the University of Florida.

Sophomore Laboratory Design

Once the course was approved for the catalog by the University Curriculum Committee, the course content could be further developed. Since the junior year focuses on characterization, and the structure – processing –properties relationships, and the senior year on processing and optimization, a natural fit for the sophomore laboratory would be structure –properties relationships, with a theme of sustainable materials design. This would allow students to conduct design work earlier in their engineering development, and to tie design to content from the introductory materials coursework.

The idea of doing engineering design early in a student's curriculum is well established[9-12], and many universities are currently implementing cross disciplinary freshman design experiences. It was also established by literature that senior design behavior has tended to be more sophisticated than freshman design behavior and seniors tended to produce higher quality design solutions than freshman when solving the same type of design behavior[12]. For the implementation of the sophomore laboratory at UF, this was taken into account in the design of the laboratory curriculum. While allowing sophomore students to design using sustainable principles, the design projects would be closely aligned to the core content knowledge they were learning during their sophomore year in order to allow them to apply this knowledge directly in context. This is hoped to give sophomore MSE students a richer design experience, and to produce high quality products from the students earlier in their curriculum, and prepare them for a more advanced senior design experience.

Using Table 1 as an initial guide for development, a grid was developed for the course, as seen in Table 2 below.

Laboratory Project	**Content aligned with the Introduction to Materials Science Course Conceptual understanding**	**Design Skills**	**Social Skills**	**Professional Skills**
Sustainable Materials past, present and future	Structure, properties, classes of materials, polymer structures, Characteristics, Applications, and Processing of Polymers	Sustainable water capture system using nature inspired design.	Work as part of a team with global partner input.	Contemporary issues and materials solutions to these problems. Engineering solutions in a global context. Understanding professional and ethical responsibilities. Need for continued learning in order to solve complex problems.
Structural materials for transportation solutions	Corrosion, failure analysis, imperfections in solids, Mechanical properties of metals, phase diagrams, phase transformations, applications and processing of metal alloys, composites	Sustainable materials for automotive and transportation needs. Design for upcycled car parts.	Work as part of a team with industry partner input.	
Materials for Healthcare and Medicine	Diffusion, Magnetism, Thermal Properties, degradation, Structure and properties of Ceramics	Sustainable materials for biomaterials applications – printable biomaterials and magnetic nanoparticles.	Work as part of a team with graduate student partner input.	

Materials for Energy needs	Electricity, imperfections in solids, optical properties	Sustainable materials for energy- LEDs	Work as part of a team with industry partner input.	

Table 2: Content Alignment with Laboratory Objectives based on ABET aligned laboratories.

This new frame provides the basis for development of individual activities aligned to best practices. These are shown later in Table 3. Each activity has a first week "kickoff session" where students are introduced to the design challenge and have a speaker, industry "client", or professor to introduce the materials issue aligned with the challenge. Each of these entities becomes an outside resource who helps teams meet constraints and criteria for the project, and to whom students will report design progress in technical reports. Students will complete a pre-reading assignment prior to the lab, and have selected readings each week that they will need to summarize and report out on in a group style meeting format in order to build and support core content knowledge integration from the Introduction to Materials Science course with societal issues related to the design project.

Students will go through a series of short labs in order to provide technical knowledge, vocabulary and skills for their design challenge. Each laboratory activity is designed as a rotation where students will rotate in small groups to perform the experiments. During these laboratories, emphasis will be placed on the structure-properties relationship for the materials being studied. Students will be drawn back to the core content from their introductory materials course to support their concept development.

Students then enter the design activity phase, where they will design and test materials for desired properties. Students will create and test small prototypes, and test these prototypes using ASTM or experimental standards. Students will analyze their data to share and report to their outside resource. During the design phase students will use the Granta CES pack to screen materials, as well as to determine aspects related to Life Cycle Analysis (LCA) for the production of the materials.

Assessment of Sophomore Laboratory

Student products are import aspects of laboratory experiences that solidify the design experience for the students, and allow for student assessment. In the sophomore laboratory, student products will be laboratory/design notebooks, design projects & presentations (oral and written). These products build towards development of an engineering professional capacity through the writing, speaking and communicating in the ways of a professional engineer. Every student product will have a rubric for preparation and scoring, and an exemplar so that students can compare their work to a standard.

For the first year (spring 2017) students will report back through a survey tool currently in development to assess the efficacy of the activities and design project. The curriculum will be refined and pilot-tested over the summer for the next implementation cycle.

Themes for Sophomore Laboratory Activities

It is envisioned that themes and activities can be changed or strengthened to support student core MSE concepts related to the introductory materials science course, and that the design projects can be changed or aligned to better serve students and department curricular needs based on feedback, as well as in addition to being adjusted for current societal issues, including cutting-edge engineering applications that are not yet described in textbooks. Below are working examples of the way the themes are applied to support core content in the Introduction to Materials Science course, and build design, technical and experimental skills in students.

Sustainable Materials past, present and future	
Weeks	4
Experiments aligned with content goals	Porosity of materials. Density of materials related to structure. Patterning of polymers for desired properties Polymer characteristics and properties experiment. Polymer Crystallinity experiment. Experiment in surface tension and wetting.
Techniques/Tools	Archimedes density, Differential Scanning Calorimetry, Ceramic Processing and firing, Scanning Electron Microscope, polymer and ceramic templating,
Design Activity	Students will use Granta Software to analyze desired materials for testing. Students will skype with other students to find constraints and environmental parameters. Students will test fibers in a fog chamber and refine fibers for retesting. Students will test materials for water storage
Related Activities	Visit to University Museum of Natural History and tour and discussion with scientists at the museum. Skype talks between engineering students in US and in Columbia, Brazil or Nigeria. Skype talk with engineers on the Warka Water project[13]
Selected Readings	Selected readings[14-18]
Assessed Student Product	Design model and prototype of a water capture system based on nature. Students will share model with international student partners.

Structural materials for transportation solutions	
Weeks	4
Experiments aligned with content goals	Fiberglass and Carbon fiber layup Fiberglass and Carbon fiber mechanical testing Characteristics of metals and alloys. Phase and TTT diagrams for alloys. Failure analysis in materials Microstructure and metallography Corrosion testing of metals Upcycling of materials
Techniques/Tools	Scanning Electron Microscope, metallographic techniques, Charpy Impact

	testing, 3 point bending, fatigue testing, tensile testing, Creep
Design Activity	Students will use Granta Software to analyze desired materials for testing. Students will conduct a LCA for the materials used in the project. Students use case studies from readings to redesign one of the applications for upcycling and reuse. Students will test materials that have been upcycled and recast for properties meeting design constraints. Students will test materials for use in light weight cars that can be upcycled for reuse.
Related Activities	Skype talk between automotive engineers and students. Skype talks between metals recycler. Skype talk with metals producer. On campus demonstration with a light weight car for students to examine for use of materials. Tour of on campus SAE race car team facilities.
Selected Readings	Selected readings [19-23]
Assessed Student Product	Design and test materials for use in lightweight cars for strength and ability to be upcycled. Re-design a car part for a light weight car part that is made from upcycled material, or can be recovered later for upcycling. Students will share designs with industry partners.

Materials for Healthcare and Medicine	
Weeks	4
Experiments aligned with content goals	Diffusion of gases through materials, permeability of polymers Thermal effects on materials structure and properties Ferro-fluids and properties Structure and Properties of ceramics Properties of materials on the nanoscale pH effect on biomaterials Biomaterials interfaces Biomaterials and nanoparticle printing
Techniques/Tools	Vibrating sample magnetometer, oxygen sensors, UV-Visible spectrophotometer. pH measurements, 2 & 3 D printing, UV crosslinking of polymers, AFM
Design Activity	Students will use Granta Software to analyze desired materials for testing. Students will design Inkjet Printing of Flexible Electronics for Body-Worn Medical Devices
Related Activities	Introductory talk by professors doing materials research with biomedical/biomaterials applications.
Selected Readings	Selected readings [24-29]
Assessed Student Product	Design and test materials for use in printing of body worn medical devices. Students will share design with graduate students and professors through a

	poster session.

Materials for Energy Needs	
Weeks	4
Experiments aligned with content goals	Basic Circuit construction and measurement, Data Acquisition using LabVIEW, I-V of Light-Emitting Diodes, I-V of Photovoltaic Cell, Determination of wavelength of an infrared LED, Contact resistance, Make a simple OLED
Techniques/Tools	Multimeter, power supplies, XRD, SEM, IV characterization
Design Activity	Students will use Granta Software to analyze desired materials for testing and to do a LCA for the materials used in creating the proposed LED. Students will design a new color LED.
Related Activities	Introductory talk by professors making LEDs and OLEDs Weekly Skype talks with industrial engineers making LEDs, and OLEDs.
Selected Readings	Selected readings [30-34]
Assessed Student Product	Design an LED for a new color not yet produced on the market with an LCA analysis. Students will share design with industry partners.

Table 3: Overview of Laboratory progression aligned to laboratory objectives.

Conclusion

This paper looks at how laboratory curriculum was developed within the Materials Science and Engineering Department at the University of Florida to support students early in their engineering coursework. The course under development explores the materials tetrahedron for metal, ceramics, polymers, composites, and is centered on themes of sustainability, design, and engineering challenges for societies. The laboratory course is aligned to the Introduction to Materials Science course, and supports core concepts in the course. Within the laboratory, case studies, Granta CES software, laboratory and design activities supported by selected readings are used to provide relevance for the concepts for materials science students early in their academic career, and to incorporate best practices for student learning. Student work will be supported and graded using rubrics and exemplars, and an assessment tool is being developed to provide tuning feedback in order to refine the laboratories in future years.

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