Session TA2-1

Classroom-wide Student-led Undergraduate Research Experience for the Introductory Materials Science Course

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Abstract

Of the fourteen grand challenges for engineering identified by the National Academy of Engineering, at least half require design and development of new materials. Since materials are critical technology enablers, introductory materials science courses are fundamentally important for all engineering majors. Therefore, two mechanical engineering faculty members at Texas A&M University have significantly restructured the introductory materials science course to emphasize undergraduate student research projects. These research projects ask student teams to pose a research question to be addressed, develop a methodology for addressing the question, prepare a proposal for their research, carry out the research, and provide written and oral reports at the end of the semester. Radically different from approaches that emphasize coverage of a large collection of facts and concepts about the behavior of matter of topics, this process offers an alternative for introductory material science courses. The paper reviews the rationale for the change, describes how the process was implemented, and presents the preliminary results that have been obtained to date.

Introduction

Now more than ever, the U. S. faces a number of challenges that threaten current standards of living as well as the sustained competitiveness of the American economy.[1] Many of these challenges are technological in nature and while the U. S. has been at the forefront of technical innovation for more than a century, current trends indicate that the U. S. faces increasing competition from other countries[2]. To face current challenges, the U. S. needs to improve STEM education for all undergraduate students[3]. This is particularly important in the case of introductory courses, which are critical for the long-term retention of undergraduate students within STEM majors[3].

Of the fourteen grand challenges identified by the National Academy of Engineering, at least half require design and development of new materials[4]. Decreasing dependence on fossil fuels, for example, requires considerable improvements in the materials that are used in alternative energy generation technologies. From improved photovoltaic semiconducting materials with broader absorption ranges[5], better materials for interconnects, electrodes and electrolytes for solid oxide fuel cells[6], to novel hydrogen storage materials with enhanced carrying capacity[7], materials development is critical for these technologies to come to fruition. Due to the importance of materials as technology enablers, introductory materials science courses are fundamental for engineering students, regardless of their major. Unfortunately, materials science courses are perceived as difficult by many students[8], in part due to the fact that they are mostly taught as a very large collection of facts and concepts about the behavior of matter. In this way, they mirror student perceptions of introductory physics courses[9]. Content-based approaches to teaching materials science make it difficult for students to organize the vast collection of facts, concepts and ideas into cognitive structures that enable them to apply the content to real-word problems with a high level of expertise. In addition, the content of introductory material science has grown enormously as the set of engineering materials has expanded and new approaches are required to achieve learning outcomes within constraints of a one-semester introductory course.

As alternatives to traditional lecture-based presentations of knowledge, interactive and research-based approaches have been found to be significantly effective at improving the learning experience of undergraduate students. Many studies have suggested that learning can be enhanced when instructors incorporate student-centered, interactive approaches[10,11]. For example, Hake[12] has shown that interactive learning experiences significantly improves conceptual understanding in introductory physics courses. Beyond interactive learning, cooperative learning approaches, in which small groups of students learn through interaction with one another has been shown to enhance learning[13]. In addition, cooperative learning activities promote development of interpersonal skills. Regarding large enrollment courses, Beicher et al.[14] have shown that active/cooperative approaches can be quite effective in large introductory courses. Their results show significantly higher levels of conceptual understanding and improved attitudes, as well as higher success rates, particularly for underrepresented groups, compared to traditional approaches. Specific research on materials science courses has shown that active learning improves conceptual understanding. In a recent paper, using a Materials Concept Inventory, Krause et al.[15] have shown that students achieve relatively modest pre-to-post gains in knowledge (15%-20%) with traditional teaching techniques in an introductory materials science course. On the other hand, students enrolled in a similar course in which the only difference was a shift towards more active, student-centered pedagogies showed significantly higher (38%) pre-to-post knowledge gains.

In addition to interactive approaches, research has demonstrated very favorable influences of undergraduate research (UR) on the overall educational experience of undergraduate students. Research suggests that UR attracts and retains talented students within the fields of science and engineering. Lopatto[16], for example, reports a study on undergraduates from 41 institutions in which a great majority of the student participating in UR experiences began or continued to plan for graduate-level education in science. Hunter et al.[17] have shown that UR experiences in which faculty and students work collaboratively on a project of common interest contribute to significant gains relating to the process of professional socialization into the sciences. Russell et al.[18] found that participation in undergraduate research resulted in increases in understanding, confidence, and awareness. Eighty-eight percent of the 3300 respondents to a survey "reported that their understanding of how to conduct a research project increased a fair amount or a great deal, 83% said their confidence in their research skills increased, and 73% said their awareness of what graduate school is like increased"[18]. Also, 68% of the respondents "said their interest in a STEM career increased at least somewhat as a result of their UR experience"[18].

More specific research on influences of UR on retention has shown very promising results. For example, Hoit and Ohland[19] showed that changing typical introductory lecture-based engineering courses into laboratory-based courses significantly improved the learning experience. Specifically, they showed that such pedagogy improves student awareness about the nature of engineering, as well as its specific disciplines. More importantly, such an approach showed improved retention of the participating engineering students. Hoit and Ohland[19] attributed the retention effect to the fact that such laboratory experiences facilitate early association of participating students with the engineering departments. This helps students to "receive discipline-specific advising, join professional society student chapter" as well as to become acquainted with engineering faculty[19].

Since current students can access enormous amounts of information about any given subject by simply consulting the Internet[20], the role of a STEM instructor may need to evolve beyond content coverage. In recent years, "the need to modify current paradigms, to reinforce not only the technical level of the instruction, but also to improve so-called soft skills, such as communication skills, teamwork, leadership and so forth"[21] has been reinforced numerous times. Engineering graduates need development in creative thinking and problem-solving. In addition to an increase in the abilities and skills of the students, it is necessary to increase students' interest in science in technology. All this is required while at the same time emphasizing the need for students to be able to graduate in four years[21]. This impressive list cannot be achieved in any single course. However, it is possible to design learning activities within a given course in which many of the improvements just described can be initiated.

Despite these findings, STEM education has not changed much, as instructors continue to deliver information to students who are passive recipients[21]. Studies of the development of desired student outcomes for undergraduate engineers suggest that traditional approaches are ineffective at promoting development of these outcomes[22,23]. In the case of introductory science and engineering courses, this is particularly troublesome since such courses "constitute a fundamental part of the undergraduate curriculum"[3]. In fact, research suggests that improving the quality of the learning experience in introductory courses is fundamental for maintaining enrollment of undergraduate students in STEM-related majors[3]. In order to provide an alternative for the important introductory material science courses, authors have applied research on pedagogies of engagement and undergraduate research described above and pioneered an approach in which the focus of the course is research projects, proposed and implemented by student teams. The following section describes the current implementation of the student-led, research-project approach.

Incorporating Student Research Projects in an Introductory Materials Science Course

Introductory materials science courses, similar to the ones taught at Texas A&M University, have been traditionally taught through lectures with minimal active student involvement. One introductory materials science course at Texas A&M is MEEN 222, Materials Science, which is a 3 credit-hour required course for all sophomore mechanical, industrial and nuclear engineering majors. The fundamental learning goal of this course is for students to be able to identify relationships between materials properties and their structure at the electronic, atomic, microscopic and macroscopic levels. Research, cited above, has shown that student conceptual understanding of materials science does not grow significantly in these types of courses. In order to help students overcome difficulties in understanding basic concepts in materials science and promote their research skills[8], the authors have implemented more student-engaged activities in MEEN 222. With an average annual enrollment of about 450 students, MEEN 222 is one of the largest courses in engineering program. Many concerns have been raised about the feasibility of using many types of student-active pedagogies in large enrollment courses. Therefore, MEEN 222 offers an important testing ground for an approach that emphasizes undergraduate student team research projects.

MEEN 222 had been traditionally taught at Texas A&M University through series of lectures (3 hours lecturing for 15 weeks) without any laboratory demonstrations or course project activity. The authors have redesigned introductory material course by adding a new group activities, namely research *projects* laboratory *demonstrations*. For those activities, students are supposed to form teams of 5-8 membranes voluntarily (usually 9-12 teams per class) and carry out research and experimental work independently, only with only guidance and logistic support from course instructors. The aim of the efforts was to shift the emphasis away from lecture to active student engagement, which should lead to better learning of materials science.

In the *laboratory demonstrations* students spent 3 class hours during one week in the materials characterization laboratory carrying out tensile testing of steel, aluminum alloys, polycarbonate, as well as 4-point bending testing. The laboratory report are graded by instructors with maximum 10 out of 100 total course points (55 points tests + 20 points weekly quizzes + 5 pints laboratory assignment + 10 points research projects). The laboratory demonstrations are organized at the middle of 15 weeks semester.

For the *research projects*, student teams propose a research question, prepare research proposal for the project, develop and implements a methodology to address the question, and prepare oral and written reports on the research. Each team was expected to select independently during the first 4 weeks a research topic that both reflects interests of the members and illustrates some of the concepts or phenomena either taught in the class or related to materials science in general. Student teams carry out these independently-conceived experimental and theoretical research projects out of class and present their results in the class, at the end of the semester. All group members are required to participate in the 15 minutes long presentations of the group research project, which typically take place during the last three lecture hours of the semester. This class activity is graded by instructors and classmates with maximum 10 out of 100 total course points (55 points tests + 20 points weekly quizzes + 5 pints laboratory assignment + 10 points research projects). We would like to note that due to the broad variety of concepts, introductory materials courses such as MEEN 222 are ideal for the early involvement of undergraduate students in the research experience. These courses offer a wide assortment of course-related topics from which student teams can select their research projects according to their interests.

Over the past two years, over 320[1] undergraduate (mostly sophomore) students were involved in undergraduate research experience through the student-led projects and laboratory assignments

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[1] Typically, MEEN 222 students are divided into five sections, three sections offered during the Fall semester, while two are offered during Spring with Arroyave and Radovic teaching one section each per academic year.

in introductory materials science course. Students attending five out of fourteen MEEN 222 sections had research projects and laboratory demonstrations as additional class activities. More than 69 different topics in materials science were covered by those projects, such as the following:

- "**Alternative materials for skateboard griptapes** " – where students studied possibility of using different materials as alternatives to silicon carbide based griptapes for skateboards (see Figure 1**)** [24];
- "**Is it Solid or Liquid?" –** where students inspired by recently published paper[25] studied behavior of non-Newtonian solids when exposed to vibrations at different frequencies[26];
- "**Resistivity and Temperature**" – where students tested the hypothesis that the electrical conductivity in metals and alloys increases with temperature (see Figure 2**)** [27];
- **"Ferrofluids"** – where students studied behavior of ferrofluids of different viscosity in rotational magnetic fields of varying strength (a video[28] of their experiment can be found on youtube.com)[29];
- **"Pyramids and Geopolymers"–** where students tested a recent hypothesis[30] that Egyptian pyramids were built from man-made limestone block using geopolymers as a binder[31];
- **"Making Graphene"—**where students, inspired by a Popular Mechanics magazine article, attempted to generate multi-layer graphene sheets[32];
- **"Radar Absorbing Materials"** –where students investigate the effects of material surface properties, shape and configuration on their radar absorbing behavior[33];
- "**Conductive Glass**" – where students investigated effect of temperature on conductivity of borosilicate glass[34];
- "**Fun with Thermite**" – where students explored possibility of using thermite for welding and cutting different metals[35].

Figure 1. Selected slides form the presentation of the project "Alternative materials for skateboard griptape[25].

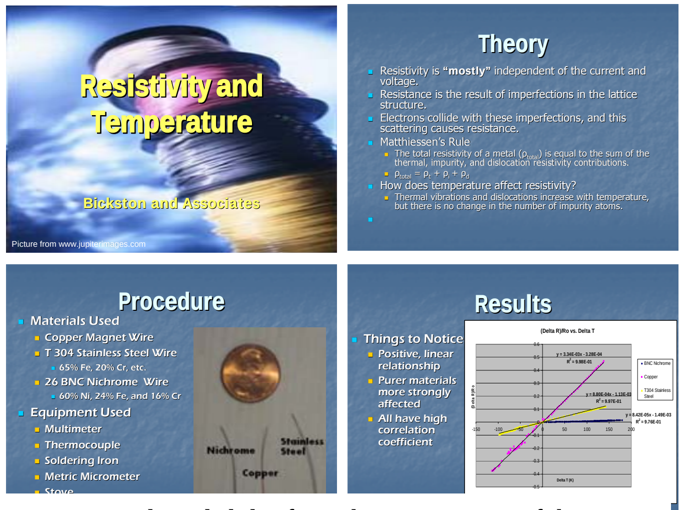

Figure 2. Selected slides form the presentation of the project "Resistivity and temperature" [27].

As the examples listed above illustrate, some of the projects explored physical materials phenomena; some of them were related to processing and application of different materials; and some of them focused on concrete technical problems. However, the diverse projects were challenging and often involved cutting edge problems in materials science. Based on written and oral reports, Arroyave and Radovic found that students had acquired a deep understanding of the relevant material science concepts directly related to their project as well as the ability to plan and implement research to investigate their hypotheses.

Student Perceptions of the Effects of Different Materials Science Course Activities

To help understand influences of student projects on learning in the course, the authors conducted an informal survey of student perceptions of the effects of different course activities during Spring and Fall 2008 semesters. Survey questions asked students to evaluate the influence of various course activities on achieving learning outcomes, development of desirable skills, interest in science and engineering, motivation, and career goals. One hundred, seventy-four (174) students from three different sections of MEEN 222 voluntarily participated in the survey and rated on the scale from 1 (lowest) to 5 (highest**)** effectiveness of the more traditional course activities such as lectures, homework, quizzes and exams, as well as newly implemented activities such as Laboratory Assignments and Research Projects**.** Table 1 shows survey results. It has to be emphasized here that the survey uses only on the students' perception on the effect of different course activities. *At this moment we do not have results of any direct assessment on the effects of different course activates on learning outcomes, skill development or interest in science and engineering.*

Based on student perceptions, independent projects (the rightmost column in Table 1) have slightly higher influences when compared to the more traditional course activities on achievement of learning outcomes such as understanding fundamental relationship between structure and properties of materials (Question 1), than other course activities, understanding differences between different types of materials (Question 2), and developing ability to select the proper material for particular application (Question 3). However, for the rest of the questions (Questions 4-12) independent projects received scores comparable only to laboratory assignments. Scores for both activities are higher than scores for other, more traditional class activities such as lectures, homework, quizzes and exams. The laboratory assignment is another new group activity added to the course by the authors. In this course activity students carry out assigned tensile tests and 4-point bending tests on instructor-selected metals and polymers. Based on their results, observations and instructions from the instructor, student teams are expected to present and analyze results in the form of written report. Laboratory assignments are worth 5 points out of 100 total possible points. According to students' opinion, both newly implemented group activities (two rightmost columns in Table 1) certainly had noticeable effect on improvement of students' skills (Questions 4 and 5). Most of the students responded that student-led projects and laboratory assignments had highest influence on development and improvement of their writing (Question 4a) and communication skills (Question 4b), ability to work in teams (Question 4c).

This is not surprising, since those activities include team work and preparation of reports and presentations. When asked to what extent each of the class activities fosters their critical thinking most of the students ranked laboratory assignments and independent projects close to other assessment activities such as homework, quizzes and exams.

Furthermore, independent projects and laboratory assignments also had the greatest influence on students' interest in science and engineering (Question #6). When asked to rate the effect that certain course activities had on their confidence level about their knowledge and ability to solve engineering problems (Question 7 in Table 1), students participating in survey gave the highest score again to the to laboratory assessments and independent student-led projects. This result is in the good agreement with previous studies that showed increase in confidence, and awareness among the students exposed to the research experience[18]. Out of 174 students participating voluntarily in the survey, 96.5% is planning to continue undergraduate education in engineering, 46.5% is planning to enroll in graduate engineering programs, and 94.2% wants to pursue their carrier in engineering. When asked to rate the effect that different course activities might have on their decision to pursue a career or education engineering (Questions 8-10), laboratory assignments and independent project again got the highest average score. The result agrees with previous studies[16-18] according to which early involvement of undergraduate students in research, activities increases their interest in continuing education and perusing carriers in engineering.

Finally, students indicated that project and laboratory activities generated the most interest (Question 11) and might most strongly affect their decision to take other material science courses in the future (Question 12). In the end, it is worth emphasizing that when asked to write what they liked the most about project work, most of the students mentioned freedom in selecting topics of their interests and carrying out research independently, and having hands on experience. Also, some students mentioned that learning from other student's project presentations was something that they liked the most about individual projects. Among the things that some of the students mentioned as the thing that they liked the least about project work were the large amount of time that they spent working on the project and in some cases the relatively large teams.

Table 1 Results of the survey in MEEN 222 class, 2008

	Question	**Average** ± standard deviation on 1-5 scale: 1 – lowest, 5 – highest					
		Lectures	Homework	Quizzes	Exams	Laboratory Assignment	Project
1	To what extent did the following course activities help you to understand fundamental relationship between structure and macroscopic physical properties and microscopic causes?	**3.23** ± 1.10	**3.42** ± 1.16	**3.48** ± 1.11	**3.46** ± 1.04	**3.74** ± 1.15	**3.60** ± 1.12
2	To what extent did the following course activities help you to develop an understanding of the differences between the different types of engineering materials in terms of their structure, properties and applications?	**3.70** ± 1.03	**3.31** ± 1.21	**3.26** ± 1.17	**3.40** ± 1.11	**3.84** ± 1.11	**3.71** ± 1.12
3	To what extent did the following course activities improve your ability to select the proper material for a specific application based on the relevant properties?	**3.47** ± 1.12	**3.16** ± 1.24	**3.10** ± 1.12	**3.12** ± 1.14	**3.77** ± 1.06	**3.66** ± 1.14
4	How would you rate the contribution of the following course activities to:						
	(a) Improvement of your writing skills?	**1.86** ± 1.01	**1.88** ± 0.96	**1.99** ± 1.01	**2.07** ± 1.06	**3.20** ± 1.36	**3.11** ± 1.35
	(a) Perfection of your communication skills?	**1.87** ± 1.05	**1.85** ± 1.04	**1.94** ± 1.06	**2.00** ± 1.14	**3.06** ± 1.40	**3.68** ± 1.27
	(a) Strengthen your ability to work as a part of the team?	**1.84** ± 1.13	**2.08** ± 1.25	**1.98** ± 1.23	**2.06** ± 1.27	**4.22** ± 1.07	**4.19** ± 1.14
5	To what extent did the following course activities foster your critical thinking?	**2.93** ± 1.20	**3.44** ± 1.31	**3.71** ± 1.15	**3.95** ± 1.22	**3.67** ± 1.15	**3.80** ± 1.17
6	Please assign a rate to each of the activities based on whether they increased your interest in research in science/engineering.	**3.00** ± 1.30	**2.40** ± 1.23	**2.37** ± 1.23	**2.38** ± 1.32	**3.71** ± 1.28	**3.77** ± 1.26
7	To what extent did each of the course activities make you feel more confident about your knowledge and capabilities to solve engineering problems?	**2.94** ± 1.22	**3.21** ± 1.28	**3.24** ± 1.20	**3.29** ± 1.27	**3.59** ± 1.06	**3.67** ± 1.12
8	To what extent your decision to continue undergraduate educational in engineering might be affected by each of the course activities?	**2.67** ± 1.34	**2.40** ± 1.25	**2.52** ± 1.28	**2.69** ± 1.43	**3.17** ± 1.43	**3.20** ± 1.45
9	To what extent your decision to enroll graduate program in engineering might be affected by each of the course activities?	**2.54** ± 1.39	**2.32** ± 1.26	**2.45** ± 1.31	**2.49** ± 1.42	**2.97** ± 1.48	**3.05** ± 1.54
10	To what extent your decision to pursue career in engineering might be affected by each of the course activities?	**2.75** ± 1.33	**2.52** ± 1.29	**2.43** ± 1.24	**2.49** ± 1.30	**3.30** ± 1.43	**3.35** ± 1.45
11	Rate your level of interest in the following course activities.	**2.85** ± 1.34	**2.43** ± 1.30	**2.51** ± 1.27	**2.65** ± 1.38	**3.85** ± 1.24	**3.85** ± 1.24
12	Based on your experience with MEEN 222, rate the course activities listed below that might affect your decision to take any other course in the future?	**2.88** ± 1.30	**2.59** ± 1.20	**2.71** ± 1.23	**2.90** ± 1.32	**3.37** ± 1.29	**3.39** ± 1.32

Conclusions

Over the last two-and-a-half years, more than 320 undergraduate (mostly sophomore) students experienced an undergraduate research experience though unconventional class activities within the introductory Materials Science course (MEEN 222) at Texas A&M University. Newly implemented class activates included *student-centered and student-led, classroom-wide research projects* (Project) and *Laboratory Assignment* (Lab). In more than 69 projects with different topics in materials science students demonstrated deep understanding of the relevant material science concepts and ability to plan and implement research to investigate their hypothesis. Based on student perceptions, independent projects and laboratory assignments affected learning more than other traditional course activities improvement of their professional skills and confidence, interests in science and engineering, and decision to pursue carrier and education in engineering. Also, both activities were rated as the most interesting and ones that might affect their decision on taking additional materials science courses in the future.

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