Bad to the Bone: Multifaceted Enrichment of Open-Ended Biomechanics Class Projects

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Equipping engineering students for career success requires more than technical proficiency; mindset and contextual interpretation also matter. Entrepreneurial mindset learning (EML) is one framework that faculty can use to systematically enrich course projects to encourage development of these important career skills. We present the thought process behind enriching two biomechanics class projects to foster both the entrepreneurial mindset and the technical proficiency in undergraduate engineering students. One project required students to analyze a court case surrounding vertebral fracture in an elderly woman diagnosed one year after a fall in an elevator. In addition to technical analysis, students had to make a recommendation about the likelihood that the injury occurred due to the fall, and contextualize the results within economic and societal terms—how much should the plaintiff sue for and how could such injuries be prevented through design and regulation? The second project asked students to evaluate cervine cancellous bone as a suitable laboratory model for biomechanics research. In addition to technical analysis, students considered the value of cervine vertebrae as a laboratory model within the context of societal and economic benefits of ex vivo animal models, including the relevant policy and regulatory issues. In both projects, implemented at different institutions with similar student demographics, students performed well and enjoyed the "real-world" nature of the projects, despite their frustrations with the open-ended nature of the questions posed. These and other similar projects can be further enhanced to foster the entrepreneurial mindset in undergraduate engineering students without undue burden on the instructor. [DOI: 10.1115/1.4040293]

Keywords: active learning, vertebral fracture project, bone microstructure project, entrepreneurial mindset learning

Introduction

While traditional engineering classes offer students the opportunity to develop technical proficiency and problem-solving skills, it has been long recognized that these are necessary, but not sufficient, for a successful career [1]. Indeed, successful engineers also possess "soft skills" such as adaptability, excellent written communication [2,3], conflict management, critical observation, and the ability to work in teams [4]. But even these are not sufficient in today's global economy [5], where the average engineer works for three different companies during their first five years of employment [6]. Many argue that success in the 21st century requires the creativity, adaptability, and flexibility embodied by an "entrepreneurial mindset" [7–9].

The entrepreneurial mindset describes an approach to solving problems through emphasis on innovation, resourcefulness, and value creation, all in the context of broader societal impacts. Individuals who possess an entrepreneurial mindset do not necessarily go on to become entrepreneurs, but are successful in whatever career they choose because they are, by definition, more resourceful and adaptable. Entrepreneurial mindset learning (EML), as championed by the Kern Entrepreneurial Engineering Network, offers a framework for faculty to consider ancillary outcomes (beyond technical proficiency) such as stimulating curiosity, making connections, and creating value [10] in the context of engineering teaching. Integrating EML activities into more traditional, lecture-based classes with technical outcomes can be challenging. For example, using a flipped classroom or entirely project-based learning to infuse EML into the curriculum requires 30–70% more time on the part of the instructor [11], and many instructors feel ill-equipped to include EML due to their own lack of training [7]. Engineering design courses are well-positioned to be enhanced by EML activities due to the nature of their outcomes. These courses are often effectively taught using problem- or project-based learning [12] and typically feature open-ended real-world problems which can be further enhanced by considering elements of EML [7]. The use of a needs-approach-benefits-comparison (NABC) method to enhance real-world context in these courses has been previously described [7] in which traditional engineering projects were enriched by asking students to identify these elements of the project. The projects described in this paper take a similar approach to infusing elements of EML into the biomechanics classroom.

Bioengineering and biomechanics education inherently includes many aspects of EML alongside the development of technical proficiency. In these disciplines, students must learn about biocompatibility, ethical decision making, and other issues unique to working with humans and animals. Many bioengineering problems used in the classroom include realistic and contextual constraints. As such, they frequently spark excitement in students who can immediately see the real-world application of their coursework. Consideration of the Entrepreneurial Mindset as a framework when developing course projects offers faculty a structure to further enrich content and benefit students [13].

Here, we present a framework for developing biomechanics class projects that incorporate EML with deliberate, simple enhancements. We also discuss how more traditional assignments can be enhanced to add EML principles with only minor changes. Finally, we provide descriptions of two instructors' class projects. In each project, specific EML principles were identified and incorporated into a primarily technical project related to bone mechanics.

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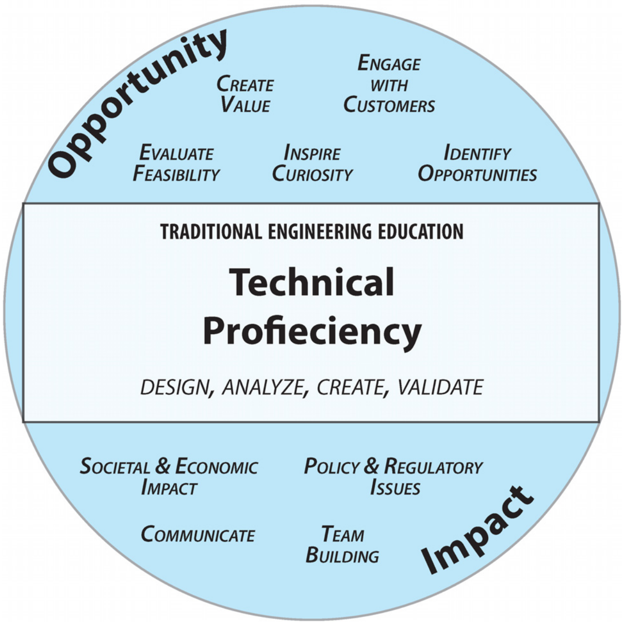

Fig. 1 Highlights of EML concepts in relation to traditional engineering education

Methods

Framework. Open-ended and deliberately ambiguous projects offer students the opportunity to "puzzle" over a real-world problem. Framing such projects requires careful consideration of learning outcomes by the instructor. A well-written project provides a goal for the student. This serves as a context and stimulus for learning that can improve understanding [14].

Below, we outline a sequence of steps that can be used to develop or modify student projects to enhance real-world context and increase student curiosity. These are based on established principles for developing student-centered learning activities using backward design [15]:

1. *Consider the context of the project*. How many students? Will the project be done in or out of class? Will it be a major or minor part of the course grade?
2. *Identify learning goals for the project*. For EML projects, these typically include a mix of technical knowledge, communication skills, and EML skills (see Fig. 1). It is often useful to think about Fink's taxonomy of Significant Learning [16] both during this stage and while designing activities. Specifically, consider the key *information*, *ideas*, and *skills* that you hope students will remember *one or two years* after they complete the project.
3. *Consider how you will assess learning*. How will students demonstrate they have successfully met your learning goals?
4. *Design a real world activity that simultaneously addresses all learning goals*. Project- and problem-based learning are well-suited to engage students with real-world problems. Often, this is a fundamentally technical problem introduced with a contextual "hook," such as a story or case study. Projects can be easily tailored to integrate technical and nontechnical skills, while stimulating student curiosity and connections.

The authors systematically enhanced biomechanics class projects with EML tasks. In each case, the technical nature of the project was preserved and enhanced. Specific highlights from EML-enhanced case studies are described later in the context of the four-step process outlined earlier.

Project 1: vertebral fracture project, the elevator problem. (KLT at Worcester Polytechnic Institute)

Project context. This project was delivered in a junior/senior level Biomedical/Mechanical Engineering course enrolling 40 students. Students worked in assigned groups of four for the project, which occurred over a 3-week time period, including 2 h of class time. The project was worth 20% of the final course grade.

Learning goals. This project had the following learning goals:

1. Apply technical biomechanics knowledge to a real-world problem.
2. Develop a reasonable approach to dealing with uncertainty and the need for assumptions, and evaluate the plausibility and feasibility of proposed solutions.
3. Communicate findings in terms of economic and societal costs and benefits.

Learning assessment. A report (no more than eight pages double spaced, including calculations) was turned in. Students were also responsible for briefly explaining their expert opinion and summarizing their assumptions in front of the class. A rubric, provided to students at the time the assignment was distributed, was used for grading. Out of 100 total points, 40 were assigned to technical correctness; 20 for clear written communication, organization, and professionalism; 25 for using realistic information, dealing with uncertainty, and providing context for assumptions; and 15 for providing answers to specific questions.

Project description. Students were given the following scenario: "You are a biomechanics expert witness for an accident case. Mrs. Albert was riding in an elevator when it suddenly screeched to a halt between floors. A second later it free-fell 6 feet and abruptly came to a halt. Mrs. Albert felt sore and received an X-ray later that day, which showed no fracture. One year later she was diagnosed with multiple vertebral fractures and opted to sue the elevator manufacturer."

The final goal of the assignment was to write a one-paragraph expert opinion, supported with data, summarizing whether it was more likely than not that Mrs. Albert's vertebral fractures were caused by the elevator accident. Groups also orally presented two slides to the class, which described their approach and key conclusions.

EML enhancements. Throughout the development of the project, the Entrepreneurial mindset was considered [10]. In addition to traditional engineering project goals of *performing analysis* and *validating* results, this particular project met entrepreneurially minded learning goals in the following ways:

- Students were not told who they worked for; if prompted, half the teams were told they work for Mrs. Albert, while the other half worked for the elevator company. The best student groups *created value* for their customer, in the context of *professional ethics*.
- To determine whether Mrs. Albert had a viable case, students had to *assess policy and regulatory issues*.
- Students had to understand vertebral structure and function, and the engineering design of elevator braking systems. This prompted them to search both research and technical literature, and allowed them to *analyze their solutions* in a real-world context.
- Students had to *consider the economic implications and laws governing workplace injuries* to make a recommendation about how much Mrs. Albert should sue for.
- Students *identified opportunities to improve safety in product design, considering societal impacts;* they were asked to discuss how this injury could be prevented in the future, given that elevators were necessary.
- By writing an expert opinion, students learned to *communicate their engineering analysis in terms of economic and societal benefits* (or costs, in this project).

Instructor role. During the first class period (approximately 40 min), groups were prompted to discuss mechanisms of injury, and to brainstorm questions, they needed to ask and answer to determine whether Mrs. Albert had a case. These questions were shared with the class in a call-out format. The instructor compiled the list into a document and then led a discussion about the role each possible question might have in solving the problem. For example, students often wanted to know about what Mrs. Alberts did during the year between her X-ray and her complaint, or about the credentials of the technician who performed the X-ray. While these are important questions for the lawsuit itself, they are not relevant to the question the students needed to answer, which focused on whether it was possible for the accident to cause a fracture. Students were guided toward the information pertaining to the amount of force that was experienced and the strength of the bone in question.

One week later, students were provided with results from Mrs. Albert's most recent bone density scan, as well has her age, height, weight, occupation, and health history. An additional 15-min period during class was devoted to discussing possible approaches and assumptions. Students were instructed to provide context, rationale, and citations (if available) for any values they assumed. They were advised to consider the problem in terms of upper and lower limits. The week before the project was due, groups were offered an opportunity to meet one-on-one with the instructor to go over their approach and rationale. Responses to common questions were posted as class announcements in the online learning system (Canvas).

Project 2: Cervine cancellous bone microstructure analysis. (LK at Clarkson University, Fall 2016)

Project context. This project was implemented in a primarily upper division undergraduate biomechanics course. Students (26 total) worked in assigned groups of three and completed this project over seven classroom instructional periods (approximately 2 weeks of class time), plus additional out-of-class work time as needed. The project was worth 10% of the overall course grade.

Learning goals. This project had the following learning goals:

(1) Apply technical biomechanics knowledge and modern analysis software to an open-ended real-world problem.
(2) Use engineering and scientific judgment to choose an appropriate analysis.
(3) Professionally communicate methods and findings in writing, including the economic and societal costs and benefits.
(4) Critically analyze the work of others.

Learning assessment. Each group was instructed to design their own technical analysis, and the depth of this analysis was considered in their project grade. For example, groups had to consider how many samples of bone to analyze, how many times would they analyze each vertebrae, and whether they would analyze any additional parameters beyond those required. Student groups also had to decide how to summarize and present their results, and how they would validate the realism of their output. Each group delivered a report, structured similar to a journal paper, and reports were peer reviewed in class. After receiving peer feedback, student groups could revise their reports for additional credit. To earn a grade of an "A," students had to exceed the minimum requirements by completing additional analysis of their choosing, thoroughly comparing their results to the literature beyond that provided, and discuss the importance of the research question within societal contexts. Students completed a peer-evaluation survey in CATME [4], demonstrating their ability to evaluate their work in teams. The assignment was graded out of 100 points total. Of these 100 points, students earned ten points for completing the CATME peer evaluation surveys (once for the Analysis report and once for the peer review), 50 points for the analysis report, and 40 for the peer review. Standard deductions were applied to the group score for missing progress reports (−5 for each missing) or missing evidence that each student had participated in the analysis (−10). Group report scores were scaled by the individual factor from the CATME survey, creating an individual assessment. Up to five points of extra credit, applied to all students in the group, were awarded to groups who revised their analysis report based on the response to the peer review and included a memo describing their revisions.

Project description. Students were tasked to analyze the microstructural parameters of cervine vertebral cancellous bone based on microCT scans (generated as part of author LK's ongoing research [17,18]). In particular, all students were asked to consider the following question: "Is cervine cancellous vertebral bone microstructure suitable for use in laboratory studies of bone biomechanics?" It is important to note that this question remains unanswered in the literature; this created a sense of curiosity in the classroom. Each group was assigned a particular, unique focus of investigation and specific vertebrae to analyze (for example, comparing cranial versus caudal parameters or L2 to L4 vertebrae.)

MicroCT scans of cervine lumbar vertebrae and rudimentary instructions for using ImageJ [19] and the BoneJ plugin were provided to students. The microstructural analysis parameters included trabecular thickness, trabecular number, bone volume fraction, and connectivity density as identified by the students. As the project concluded, all groups' results were compiled into a spreadsheet, and each individual student was tasked with making an interesting observation about the data set and presenting it in a single-slide format. These slides were compiled by the instructor and shared in a class discussion.

EML enhancements. This project was enhanced, compared to a traditional technical/design-only project, to meet several entrepreneurially minded learning goals in the following ways:

- Students were forced to consider the value of an ex vivo model for laboratory research. This required them to *investigate the (research) market* and *evaluate the societal benefits* and *sustainability* of ex vivo animal models for biomechanical studies. Implementing this in the classroom required only a few minutes of discussion time to encourage students to think about this.
- Students developed curiosity about the use of cadaver specimens in research and learned about relevant *policy and regulatory issues*. Many reported that they had not previously considered the utility or value of this type of work.
- Students learned about intellectual property surrounding ImageJ (freely available research-grade software).
- Students *communicated* the *societal benefits* of their conclusion in *economic terms* in their reports.

Instructor role. In this project, the instructor introduced the project and posed the research question to the students. A handout describing the learning objectives, project logistics, grading criteria, and timeline was provided to students. A list of recommended report components (e.g., introduction, methods, results, discussion, and references) was included. The project and associated materials were crafted following discussions with other faculty implementing EML in courses. After the project introduction, the instructor primarily served as a guide to students about best practices in research and data analysis, providing general advice and ideas, but refrained from making specific recommendations (e.g., "You might want to consider repeating your measurements more than once" instead of "You should perform each measurement 3 times").

Results

These projects were implemented in undergraduate biomechanics classes at two primarily undergraduate institutions. The observations of the instructors are described below:

Project #1 was implemented in a junior/senior Mechanical Engineering/Biomedical Engineering biomechanics course over a three-week period. The version presented here included two classroom periods of worktime, plus one classroom period for discussion of the final product. Student feedback indicated both enthusiasm and frustration. Students liked the project because of the "real world application" and enjoyed that there was "no real right answer… it makes you think about every possibility." However, they found it "frustrating due to lack of definite data" and generally confusing, compared to more clearly defined problems. Several students expressed mixed (but generally positive) feelings about the group sharing. One summarized, "I liked how we all talked about what we did to arrive at our conclusion on the very last day, but it was also very intimidating as at that point it was too late to make any changes to our calculations."

Overall, students performed well on the project, with an average grade of 86/100. The majority of students performed well on the technical calculations, but many struggled with the need to justify and contextualize their assumptions. In this particular scenario, a key unknown variable is the time period during which Mrs. Albert decelerates after the elevator stops. (Deceleration time eventually influences impact force on the spine). While there was no "right answer" to this value (indeed, there is no way of knowing what it could have been), the best student reports provided a range of plausible values, along with a context for these values and cited references. The best papers also discussed limitations of the calculations and the assumptions that went into them.

Project #2 was implemented in an upper level biomechanics class over several weeks. Anecdotal observations indicate that students were highly engaged throughout the process; informal reporting suggested that many teams spent an additional 20 h outside of class time working on the project. Students performed well with an average grade of 84/100. Students were initially frustrated by the absence of a "recipe" for success in the project, and the need to make and justify their own choices about analysis methods, report contents, and report style.

Despite students' initial frustration by the unknown nature of the project and by the gaps in their own knowledge of regulatory issues and the research process, they displayed confidence in their results by the end, as evidenced by dialog between groups about choice of methods and realism of results. Students' detailed observations about the collection of data generated by all groups indicated a high level of curiosity about potential outliers and trends. For example, students were shocked that measurements of the same parameters of the same specimen by different groups often had wildly different results. Some indicated that the experience was meritous of discussion with prospective employers.

Discussion

Taken together, these biomechanics class projects provide two examples of how EML can be incorporated into otherwise straightforward technical analysis projects, without overly burdening the faculty member. Note that both of these projects were performed within classes that include lectures and other activities. That is, while both instructors use active learning methods, the courses were not entirely project-based. Others have shown that enhancing classroom projects to include skills within the entrepreneurial mindset may increase student engagement in the classroom [7], and our experience agrees with this. These enhanced projects can inspire students to build *connections* between their classroom experience and the real world, look *creatively* at problems, and *create value* through their work. For example, students in Project 1 used a wide range of approaches, both simple and complex, to support their conclusions. In particular, some groups became intrigued by the legal aspects of the case, inspiring them to research areas that were contextually relevant (e.g., elevator safety standards, medical malpractice laws, and standards for admissibility of evidence), although nontechnical. Students in project 2 made individual observations about the aggregate data set generated by the class, and discovered that trabecular microarchitecture was, or was not, correlated with specimen age, based on whether specific data points were included. Both projects included oral presentation of group data to the entire class. We believe that some sort of sharing is important for two reasons: (1) This is an opportunity for students to practice their communication skills and (2) sharing exposes students to the wide range of creative approaches their classmates take in addressing these ambiguous problems.

The projects described here required relatively minor edits from the previous instantiations to incorporate EML. Furthermore, these edits were primarily achieved by using the EML outcomes as a scaffold to add small enhancements to student requirements, many of which are synergistic with principles of good pedagogy and ABET outcomes [20]. Specifically, the instructors carefully considered each EML outcome with regard to the planned project. This often led to an interesting question, modification, or addition to the project requirements for students. However, this was done without substantially changing the scope of the assignment, recognizing that not every EML outcome will be a natural fit for each assignment. In our experience, shared brainstorming, consultation, and conversations with other instructors with similar goals are an effective way to identify easy-to-implement modifications that enhance EML in class activities. For example, in project 2, the idea of asking students to consider the value of ex vivo biomechanical models in addition to the scientific appropriateness of the model came from one such conversation. Our method has conceptual overlap with the NABC method described by Carlson and Wilmot [21], but is somewhat more versatile. While both methods emphasize value creation, the NABC method is sometimes difficult for students (and instructors) to conceptualize for projects that do not include a design element. Nevertheless, our observations of student satisfaction and response are similar to those reported for NABC-framed EML projects. That is, our students also experienced both elation and frustration with the open-ended nature of the projects. There was variability in timeliness of student work and preparation, and students perceived that the project required a considerable amount of time to complete.

Future Extensions and Conclusion. The projects presented here could be further enhanced with real-world context, including EML outcomes, using the same process described in this paper. Both project descriptions are available on the ASB Teaching Repository[2] [22] which can be found by searching for the authors by name.

Potential modifications to the elevator problem project: Details of this project could be easily modified to emphasize different technical and contextual knowledge. For example, Mrs. Albert's history could include the use of drugs that affect bone metabolism to prompt student research on bone/drug interactions. Mrs. Alberts could be given an occupation that includes repetitive activity, such as factory work, to prompt a discussion of ergonomics and occupational injury. The anatomic site of interest or the tissue of interest (e.g., heart, brain, muscle, and cartilage) could be changed to emphasize specific technical material. Students also made suggestions for the next offering of the project. These included a shift in context (e.g., referencing a particular on-campus elevator, which could then be used for experimental measurement) and adding additional elevator occupants (e.g., another passenger who did not become injured).

Potential modifications to the cancellous bone microstructure project: This project could be adapted to analyze any microCT scans of cancellous bone, including clinical data. Additional animal models could be used, such as pigs, cows, or monkeys and students could be asked to evaluate the use of each animal within the context of animal welfare standards, scientific suitability, and ethical considerations. The technical analysis could be extended to include both cortical and cancellous bone measurements. Students could be asked to consider the scientific, societal, and ethical considerations of using bones from sick animals (such as those that are too sick to slaughter) in research. Students could be asked to consider the supply chain and distribution methods, including the relevant transportation policy issues, of using deer bones in

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[2] http://asbteachingrepository.herokuapp.com/

research, which are regionally and seasonally abundant in some locales. Future changes to the structure of the report could require students to revisit (and perhaps recompute) their results after comparison with those of other groups or to assess the certainty of their results. The project could also be modified to use different software and imaging methods to analyze the crimp period of collagen fibers in soft tissue.

Mitigating challenges of implementing EML: The authors note that implementing curricular change, particularly toward inclusion of open-ended projects, can be poorly received by students. These instructors both emphasized the real-world nature of these open-ended questions when introducing them in class. Furthermore, it was clearly stated that the assessment would be based both on the quality of the results and the quality of the methods employed by students. Minimum expectations were set and the grading scale was described in general terms. (For example, "'B' reports will include the quantification of the required parameters (probably including multiple measurements of the same quantities), compare them to the literature (including sources beyond those provided), suggest explanations for the results, include a thorough discussion of the results and limitations, and describe some future work.") Giving students a clear grading rubric and autonomy to customize their analyses appeared to mitigate any discontent due to the open-ended nature of the project.

It is important to note that projects are just one of many frameworks that can be used to enhance student engagement and encourage EML both in and out of the biomechanics classroom. Other examples include discussion prompts that focus on controversial issues or that stimulate discussion of biomechanics in context, guided in-class discussions of relevant popular media articles, and "wrapping" homework problems within a broader story-telling context. In each of these examples, enhancing an assignment or project with EML requires intention and creativity, but does not necessarily burden the instructor with additional responsibilities. Many elements of EML are synergistic with fundamental principles behind problem-based learning, flipped classrooms, and other contemporary pedagogical techniques [23–25]. That is, incorporating elements of EML into existing classroom activities, such as projects, can add value and context to students with only a small effort from the instructor.

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