ABSTRACT

It is well known and widely accepted that the integration of research and teaching in a problem-based setting helps to foster deep learning among students. In this paper, we describe how a patent of a rotary diesel engine, that had failed to work in practice, was used to link undergraduate research and teaching activities by orchestrating two design courses around this patent. Learning outcomes, course goals, content as well as assignments and projects were defined based on constructive alignment. Students’ performance was assessed using so-called assessment rubrics based on Bloom’s taxonomy, which were specifically developed for both courses. After introducing the educational framework for this approach to enhancing student learning, we explain how both courses were designed and delivered in order to meet the higher level educational outcomes envisaged. The paper closes with an overview of both our experiences and those of our students.

1. INTRODUCTION

The development of Mechanical Engineering curricula and corresponding courses is a challenging task. In order to provide students with the education they need to become future leaders in their field, a number of aspects have to be taken into account. Course objectives, learning outcomes, technical content, course delivery, setting of assignments and examination papers as well as appropriate assessment procedures have to be constructively aligned [1]. This is important in order to foster deep learning among students and also to meet formal ABET requirements with regard to program accreditation.

A highly effective means to enhance student learning through problem-based educational activities is to link teaching and research by incorporating related research activities into the curriculum or a particular course. Such activities are part of the

Woodruff School of Mechanical Engineering at Georgia Tech Savannahs’ approach to strategic design of engineering education [2].

Recently, two mechanical engineering courses, ME3180: Machine Design and ME4041: Interactive Computer Graphics and CAD, for undergraduate students at Georgia Tech Savannah were orchestrated around a patent of a rotary diesel engine. The design of the revolutionary engine had been patented years ago but failed to work in practice. Finally, its inventor, Edward Morgan, donated the patent to Georgia Tech for their faculty and students to analyze the design, make improvements, and finally make the machine work [3]. In this paper, we give an overview of the educational activities that were taken to link research and teaching by orchestrating the design courses around the patent of a diesel engine. It is demonstrated how the courses were designed in order to address higher level educational objectives and to meet accreditation needs.

2. THEORETICAL FRAMEWORK

2.1 Approaches to learning

An approach to learning is mainly characterized by an intention, which is usually coupled with a process. There are different approaches to learning that a student may adopt. Broadly speaking, one may distinguish between ‘deep learning’, ‘surface learning’ and ‘strategic learning’.

The intention behind ‘surface learning’ is just to cope with the course requirements. Surface learning focuses on the superficial aspects of what is being taught. The process behind surface learning is that of reproducing information, e.g. by memorizing facts and procedures routinely.

In adopting a ‘strategic approach’ to learning, the emphasis is towards achieving the highest possible grades with minimum personal input. The process behind strategic learning is that of
organization, e.g. by managing time and effort effectively. ‘Deep learning’ is to thoroughly understand what is being taught. The focus is on what is ‘signified’, what the message is about, and what things mean. Deep learning actively involves establishing relationships between ideas, past experiences, and the real world.

Deep learning processes can be stimulated through problem-based educational activities that link teaching and research by incorporating subject-related research activities into the curriculum or a particular course. Such an approach addresses the analysis, synthesis, and evaluation domains of learning as proposed by Bloom [4].

2.2 Teaching and learning in the Mechanical Engineering context

Since learning itself is a process that is expected to produce an outcome, it is necessary to understand what students think ‘learning’ is and involves, how they actually perform their learning processes, why they learn exactly the way they do it, and what factors influence the learning process and its outcomes, both prior to initiating the learning process and along the way [5].

In order to understand student variation of learning within the specific discipline context of Mechanical Engineering, factors such as motivation and intention, conceptions of learning, learning process, subject prior knowledge, personal limits, learning environment, teaching style, etc. as well as their linkages [6] have to be considered. Overton [7] states that the Engineering disciplines are heavily content driven which often leads to overloaded curricula which in consequence encourages students to adopt surface or strategic approaches to learning. Overton also states that Problem Based Learning (PBL) is often used in Engineering as a teaching style that enforces deep approaches to learning. Dominating assessment styles in engineering are unseen written exams, written assignments or essays as well as lab projects and reports. The majority of those foster learning processes that relate to surface or strategic approaches.

2.3 Constructive alignment and Bloom’s taxonomy

Constructive Alignment, a term coined by Biggs [1] is one of the most influential ideas in higher education. It is the underpinning concept behind the current requirements for program specification, declarations of intended learning outcomes and assessment criteria, and the use of criterion based assessment. There are two parts to constructive alignment: (1) students construct meaning from what they do to learn, and (2) the professor aligns the planned learning activities with the associated learning outcomes. The basic premise of the whole system is that the curriculum is designed so that learning activities and associated assessment tasks are aligned with the learning outcomes that are intended in the course. This means that the system is consistent. Constructive alignment encourages clarity in the design of the curriculum, and transparency in the links between learning and assessment. As students learn, the outcomes of their learning display similar stages of increasing structural complexity.

In 1956, Bloom [4] developed a classification of levels of intellectual behavior important in learning. Bloom found that at the time over 95% of the test questions students encountered required them to think only at the lowest possible level, i.e., the recall of information. Bloom identified six levels within the cognitive domain, from the simple recall or recognition of facts, as the lowest level, through increasingly more complex and abstract mental levels, to the highest order which is classified as evaluation. These six levels are: (1) knowledge, (2) comprehension, (3) application, (4) analysis, (5) synthesis, and (6) evaluation (see Figure 1).

![Figure 1 – Six levels in Bloom’s taxonomy](image)

Bloom’s taxonomy provides a systematic way of describing how a learner’s performance grows in complexity when mastering academic tasks. It can thus be used to define curriculum objectives, which describe where a student should be operating, and for evaluating learning outcomes so that we can know at what level individual students actually are operating. In a truly constructively aligned curriculum it facilitates deep learning as the activities are designed for that purpose.

3. GEORGIA TECH, SAVANNAH MECHANICAL ENGINEERING CURRICULUM

3.1 An Overview of ABET

The Accreditation Board for Engineering and Technology (ABET) is a recognized accreditor for college and university programs in applied science, computing, engineering, and technology [8]. ABET specifies minimum curricula for various engineering programs and outlines educational outcomes and objectives to be met by students at graduation.

ABET regulations provides a framework for identifying a strategic vision for an academic unit and its components. It also provides an opportunity for aligning an institute’s missions and to achieve the strategic vision of the institution. Furthermore,
ABET expects the institution to institutionalize processes that facilitate continuous improvement of the quality of the education provided. In the remainder of this chapter, the following ABET related topics will be presented:

- **Educational Objectives**: describe what students are expected to be capable of about ten years after graduation.
- **Educational Outcomes**: describe the skills students will have obtained upon graduation.
- **Course Goals**: describe the specific goals of a particular course that have to be met by students in order to pass and achieve a particular grade.
- **Assessment rubrics**: authentic assessment tool used to measure students' performance.

### 3.2 Woodruff School Educational Objectives

Educational objectives describe what students are expected to be capable of about ten years after their graduation. In this regard, the Woodruff School of Mechanical Engineering has defined the following five educational objectives for their mechanical engineering program [9]:

- A. To prepare students for successful careers and empower them to be life-long learners.
- B. To graduate engineers who solve problems through analysis that is anchored in the engineering sciences and/or computational tools.
- C. To graduate engineers who are able to design engineering systems for a global economy. This necessitates the development of skills that include the ability to formulate problems, to think creatively, to communicate effectively, to synthesize information, and to work collaboratively.
- D. To graduate engineers who are able to use experimental and analysis techniques to understand engineering phenomena and/or validate them.
- E. To graduate engineers who understand their professional and ethical responsibilities to society.

### 3.3 Woodruff School Educational Outcomes

The Woodruff School of Mechanical Engineering educates students who are supposed to become leaders in industry and academia. We expect our graduates to serve the profession, the State of Georgia, and the country. The following ten educational outcomes describing what our students will have obtained upon graduation were defined [10]:

1. An ability to identify and formulate engineering problems and apply knowledge of mathematics, science and engineering to solve those problems.
2. A familiarity with statistics and linear algebra, knowledge of chemistry and calculus-based physics with depth in at least one, and the ability to apply advanced mathematics through multivariate calculus and differential equations.
3. An ability to design and conduct experiments, as well as to analyze and interpret data.
4. An ability to design a system, component, or process to meet desired needs.
5. An ability to function professionally and with ethical responsibility as an individual and on multidisciplinary teams.
6. An ability to communicate effectively.
7. Knowledge of contemporary issues and the broad education necessary to understand the impact of engineering solutions in a global and societal context.
8. Recognition of the need for and an ability to engage in lifelong learning.
9. An ability to use the techniques, skills, and modern engineering tools, to include computational tools, necessary for engineering practice.
10. An ability to work professionally in both thermal and mechanical systems areas, including the design and realization of such systems.

Course goals can be defined depending on the nature of a particular course. These describe concrete accomplishments students are supposed to achieve within the specific technical context of that particular course. All course goals act in accordance with the educational outcomes and objectives of the whole program. Usually, coarse goals relate only to an appropriate subset, not necessarily all, of the educational outcomes and objectives defined.

### 3.4 Assessment Rubrics

A so-called rubric is an authentic assessment tool used to measure students' work [11]. What is meant by ‘authentic’ is, that simply testing an isolated skill or a retained fact does not effectively measure a student's capabilities. To accurately evaluate a learners’ performance, e.g., in relation to Bloom’s taxonomy (see above), an assessment method must examine a students' collective abilities. In this sense, a rubric represents a grading guide that seeks to evaluate a learner’s performance based on the sum of a full range of criteria rather than a single numerical score. Rubrics are not only useful to professors. If handed out to students before an assignment, examination, or probably on the first day of classes, they become aware of the criteria on which their work will be judged.

Rubrics can be created in a variety of forms and levels of complexity, however, they all contain three common features which:

- focus on measuring a stated objective or goal.
- use a range to rate performance.
- contain specific performance criteria arranged in levels indicating the degree to which a standard has been met.

Developing such assessment rubrics and making them available to students provide the scaffolding necessary to help them understand how to improve the quality of their work and increase their knowledge. In general, rubrics are supposed to offer a variety of advantages as outlined in [12]:

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Rubrics improve student performance by clearly showing the student how their work will be evaluated and what is expected.
Rubrics help students become better judges of the quality of their own work.
Rubrics allow assessment to be more objective and consistent.
Rubrics force the professor to clarify his/her criteria in specific terms.
Rubrics reduce the amount of time professors spend evaluating student work.
Rubrics promote student awareness about the criteria to use in assessing peer performance.
Rubrics provide useful feedback to the professor regarding the effectiveness of the instruction.
Rubrics provide students with more informative feedback about their strengths and areas in need of improvement.

3.5 Overview of ME3180 and ME4041

ME3180: Machine Design is a junior level course at Georgia Tech, where the emphasis is on the concepts for strength based design of machine components. During the first part of the course, fundamental topics such as loading, materials, stress-strain relationships, principal stress analysis, and fatigue are covered. During the second part, these concepts are applied to the design of machine components including shafts, bearings, gears, belts, fasteners, clutches, springs, and flywheels. Machine Design: An Integrated Approach by Norton [13] is used as a textbook for this course. The course goals and rubrics for ME3180 are listed in Table 1 and Table 2 respectively.

ME4041: Interactive Computer Graphics and CAD is a senior level undergraduate elective. The course consists of two components – Computer Aided Drafting (CAD) and Finite Element Analysis (FEA). The primary objective in this course is to expose the students to CAD and FEA technology and the basic mathematical underpinnings. The course consists of three hour per week lectures, and a three hour per week laboratory. The constructs discussed in this course include overview of CAD systems, curves, surfaces, solid models, FEA procedure, stiffness matrix formulation, element assembly, solution, and practical aspects of FEA. The textbooks used in this course include [14, 15]. During the laboratory, the students model components and assemblies using I-deas [16] and perform FEA on the components to determine their behavior under loading. The course goals and rubrics are given in Table 1 and Table 3 respectively.

The assessment tools for both these courses include weekly assignments, exams, semester-long projects, and essays on learning. Weekly assignments help students to understand the concepts presented by applying them to textbook type, well defined problems. Generally, these assignments consist of 2-3 problems based on direct application of material covered during a particular week. These assignments relate to the comprehension and application levels of Blooms’s taxonomy (see Figure 1). Exams are used to evaluate the retention of the fundamental concepts covered in the course.

Table 1 - Course Goals for ME3180 and ME4041

<table>
<thead>
<tr>
<th>ME3180: Machine Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG1 – To illustrate to students the variety of mechanical components available and emphasize the need to keep learning.</td>
</tr>
<tr>
<td>CG2 – To enable students to learn how to identify and quantify the specifications and trade-offs, including tolerances, for the selection and application of components which are commonly used in the design of complete mechanical systems.</td>
</tr>
<tr>
<td>CG3 – To teach students how to apply the fundamentals of engineering science to analyze and design commonly used mechanical components to meet specifications.</td>
</tr>
<tr>
<td>CG4 – To develop in students an ability to select, configure, and synthesize mechanical components into complete systems.</td>
</tr>
<tr>
<td>CG5 – To provide an opportunity for students to learn how to apply computer-based techniques in the selection, analysis, and synthesis of components and their integration into complete mechanical systems.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ME4041: Interactive Computer Graphics and CAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG1 – To explain the basics of Geometric Modeling, Computer Graphics</td>
</tr>
<tr>
<td>CG2 – To explain the theory behind the Finite Element Method (FEM) and to provide insight into the practical aspects of FEM</td>
</tr>
<tr>
<td>CG3 – To develop skills in the design and analysis of practical engineering problems through the integration of geometric modeling, FEM and computer graphics</td>
</tr>
<tr>
<td>CG4 – To gain hands-on experience with commercial CAD/CAE software</td>
</tr>
<tr>
<td>CG5 – To underscore the differences between numerical and closed-form approaches to engineering problems</td>
</tr>
</tbody>
</table>

Table 2 - Rubrics for ME3180 Course Goals

<table>
<thead>
<tr>
<th>Goals</th>
<th>Rubrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG1</td>
<td>- Amount of new material in open-ended assignments and project</td>
</tr>
<tr>
<td></td>
<td>- Depth of new material in open-ended assignments and project</td>
</tr>
<tr>
<td>CG2</td>
<td>- Breadth and depth of issues taken into account in assignments and project</td>
</tr>
<tr>
<td>CG3</td>
<td>- Breadth of mechanical factors considered in analysis</td>
</tr>
<tr>
<td></td>
<td>- Ability to apply correct analysis procedure based on assumptions</td>
</tr>
<tr>
<td></td>
<td>- Ability to determine correct parameters to apply in analysis procedure</td>
</tr>
<tr>
<td></td>
<td>- Ability to apply analysis procedure for designing mechanical components</td>
</tr>
<tr>
<td>CG4</td>
<td>- Knowledge of mechanical components</td>
</tr>
<tr>
<td></td>
<td>- Ability to synthesize a mechanical system</td>
</tr>
<tr>
<td>CG5</td>
<td>- Effort in using simulation based design tools to design machine elements and synthesize mechanical systems.</td>
</tr>
<tr>
<td></td>
<td>- Ability to develop computer-based techniques for analysis and synthesis of mechanical components.</td>
</tr>
</tbody>
</table>
The semester long projects address the analysis and synthesis aspects of Bloom’s taxonomy. The objective in these projects is to conceptualize and design a simple machine by applying all the knowledge gained throughout this course (and in other courses). Finally, learning essays address the evaluation aspect of Bloom’s taxonomy. Williams and Mistree [17] discuss the importance of learning essays in an individual’s learning. In the learning essays, the students are asked to discuss what they learnt throughout the course and how it relates to their careers as engineers. They are also asked to critically evaluate the current state of technology (such as CAD tools), and identify the requirements for technology in the future. This encourages the students to think beyond the bounds of information presented in the course, and to create their own knowledge.

Table 3 - Rubrics for ME4041 Course Goals

<table>
<thead>
<tr>
<th>Goals</th>
<th>Rubrics</th>
</tr>
</thead>
</table>
| CG1   | - Mathematical Modeling of Curves, Surfaces, and Solids  
|       | - Modeling of Geometric Entities using Software Tools  
|       | - Transformations of Geometric Entities  
|       | - Modeling of a Physical System |
| CG2   | - Element Stiffness Matrices  
|       | - Global Stiffness Matrices  
|       | - Modeling FEM Problems on FEM Software  
|       | - Modeling a Physical System Using FEM |
| CG3   | - Modeling of a Physical System  
|       | - Modeling a Physical System Using FEM  
|       | - Content of presentation  
|       | - Fulfill team role’s duties  
|       | - Share equally  
|       | - Listen to other teammates |
| CG4   | - Modeling FEM Problems on FEM Software  
|       | - Modeling of Geometric Entities using Software  
|       | - Continuous, Self Learning |
| CG5   | - Comparison of Approaches  
|       | - Assumptions  
|       | - Ability to select |

4. INTEGRATION OF RESEARCH AND TEACHING IN UNDERGRADUATE COURSES – AN EXAMPLE

4.1 Morgan Engine Patent

Edward H. Morgan conceptualized the design of a Rotary Diesel Engine in 1985. The concept was patented by him in 1991 [18]. The engine concept consists of a circular array of cylinders that rotate in an engine cavity about the drive shaft. Individual pistons oscillate inside the rotating cylinders whereas the cylinders are mounted on a rotating plate. A fixed reference plate has intake and exhaust slots, and means for fuel injection into the cylinders. According to Morgan, the primary motivation for such a rotary diesel engine is to develop a low cost generating solution for low speed, high torque applications such as heavy equipment and construction machinery. Another potential advantage, as highlighted by Morgan, is reduced complexity due to the elimination of a many key moving parts and subassemblies, such as valves and valve springs. Morgan developed a prototype of the engine in his workshop in Savannah, Georgia. An image of the prototype is shown in Figure 2.

Figure 2 – An Image of Morgan’s Rotary Diesel Engine

Unfortunately, the engine prototype has not sustained combustion since its first installation. The failure of the engine to sustain combustion is attributed to design flaws. Morgan attempted various configuration changes to the engine but has been unable to resolve the problem. The changes were mainly based on intuition and his past experience with engines. A systematic engineering analysis had not been performed on the engine to identify the weak spots. Recently, Morgan approached Georgia Tech, Savannah to seek help on the systematic engineering analysis of the engine. The project was then undertaken as a part of ME3180: Machine Design. The key objectives from the standpoint of the Morgan engine were to evaluate his design and offer possible suggestions for improvement. On the other hand, the key objectives from the educational standpoint were to learn how to systematically analyze and redesign a mechanical system. The objectives for the project were significantly inline with the course goals. The project was later continued by the same cohort of students in ME4041: Interactive Computer Graphics and CAD. The details of the project execution in ME3180 and ME4041 are discussed next.

4.2 Morgan Engine Research Project in Undergraduate Design Courses: ME3180 and ME4041

The project was undertaken by six students. After initial discussions with the instructor, the students were able to identify three critical aspects of the engine to be analyzed. These aspects include a) engine timing, b) cylinder
configuration, and c) the thermodynamic cycle. Accordingly, the overall team of students was divided into three sub-teams working on each of these aspects. Each team consisted of two students.

The engine timing project team studied the synchronization of cylinder position with respect to the injector location and injector pulse width. The students modeled the cylinder motion using simplified analytical models. Due to the nature of the cylinder motion, the students found that the amount of time the cylinders are exposed to the injectors may not be sufficient to deliver the fuel. Based on the preliminary study, one of the recommendations from the team was to use multiple injectors. The students identified the need to use software programs based on numerical approaches to account for the complexity of engine dynamics at different speeds.

The existing orientation of the cylinder is at 45 degrees to the rotating plate (see Figure 2). The pistons are cylindrical and are also at an angle of 45 degrees to the axis of the rotating disc. When the piston reaches the Top Dead Center (TDC), a significant void remains at the top of the cylinder. Although an attempt to correct this void was made by adding shims to the piston housing and extension to the end of the piston head, there was still a significant void that prevented the engine to achieve the desired compression. The use of shims also increased the manufacturing complexity of the piston head. In order to address these challenges, the students suggested alternative designs of the engine that involved reducing the angle between the cylinder and the rotating plate. The students also realized the need for creating accurate models of the engine using CAD software.

The third aspect of the project was performing analysis of the thermodynamic cycle. This aspect of the project was carried out by a group of students who were simultaneously taking the thermodynamics course. In this project, the students developed analytical equations for determining the temperature of the air-fuel mixture based on the compression achieved in the cylinders. Based on their calculations, the students identified that the temperature achieved cylinder does not reach the flash point. Based on their preliminary calculations, the students made specific recommendations for modifications to the geometry. A summary of the students’ recommendations from the project is provided in Table 4.

The same group of students continued the project in ME4041 during the following semester. The students performed assembly modeling of the core components of the engine in UGS I-deas 12 [16]. The assembly model was used to perform a mechanism simulation of the engine. A screen-shot of the model is shown in Figure 3. The parametric nature of the model supports exploration of different configurations and dimensions of the engine concepts. During this project, the students gained significant insight into the CAD modeling process. Since the same project was continued from the previous semester, the students did not need to spend a significant amount of time in understanding the problem.

<table>
<thead>
<tr>
<th>Table 4 - Summary of Recommendations of Students Working on the Rotary Diesel Engine Project</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Students’ recommendations</strong></td>
</tr>
<tr>
<td>&quot;Morgan's engine, without the insertion of metal shims, does not achieve enough compression, and therefore final temperature, to ignite the diesel fuel. It is recommended that Morgan fill in the combustion chamber to at most 2 in3 volume at top dead center, which is a around an 80% decrease in volume. This volume reduction would result in an 18.7:1 compression ratio and a 208.8ºC final temperature. This compression ratio fits with the design of a typical diesel engine. With this temperature, the fuel should ignite successfully. Our also team discovered alternative designs provide an easier platform for generating higher compression ratios. These higher compression ratios lead to higher temperatures after compression, allowing the diesel to combust.&quot;</td>
</tr>
</tbody>
</table>

**Figure 3 - I-deas Model of Basic Components of Rotary Diesel Engine**

In addition to the learning process related to machine design, the students also learnt about the nature of engineering design processes in general. Through the initial phase of analyzing and understanding the system, the students learnt how to start addressing open engineering problems. The three projects were closely related to each other. For example, the cylinder configuration affects the timing analysis, which in turn is important for the thermodynamic cycle analysis. The students also realized the importance of continual information exchange between design teams. In addition, they realized the significance of computer based modeling in design and were provided with an opportunity to apply the concepts they learnt in other courses (such as thermodynamics) to real-world machine design problems.

5. **CLOSURE**

Traditional analytical courses, such as Machine Design are often centered on textbook problem solving. This does neither provide students with real life experience nor does it stimulate
their ability to carry out research in order to solve a problem. The approach to integrating research and teaching based on a patent as described in this paper turned out to be highly effective.

Through individual projects carried out to investigate several parts of the patent, the students learnt how to think at a systems level and how to deal with open-ended problems. They had to deal with individual problems, which were orchestrated to help them understand ‘how to learn’ [17]. Within their projects, the students had to integrate several design methods taking into account real life limitations. In particular the sequential structure of the two courses ME3180 and ME4041 was very useful to help students understand design problems at a higher level of abstraction. The assessment rubrics based on Bloom’s taxonomy were given to the students at the beginning of the courses. That way, they knew exactly what they were supposed to demonstrate in order to achieve a particular grade. In this paper, we present a qualitative overview of learning by using the patent-based approach. However, a quantitative assessment of learning using the rubrics is a part of the future work.

The approach is presented for a small group of students (specifically, six students) but the same approach is also beneficial for larger classes. There are various strategies that can be adopted. The instructor can a) assign different patents to different groups of students, or b) assign different aspects of the same patent to different groups of students (as was performed in ME3180, ME4041), or c) assign the same project to different groups (thereby allowing students to solve the same problem from multiple perspectives).

6. ACKNOWLEDGMENTS

We thank Mr. Edward Morgan for providing us the continuous support during the project and access to his engine prototype for the undergraduate courses. We also acknowledge the students from ME3180 and ME4041: Alex Ruderman, Jonathan Bankston, Thomas Beal, Andrew Scripture, Robert Lafond, and Julian Stevenson for providing their insights into the Rotary Diesel Engine.

7. REFERENCES