

## ***Integrating Project-based Learning Throughout the Undergraduate Engineering Curriculum***

Richard N. Savage, Katherine C. Chen and Linda Vanasupa  
Cal Poly State University, Materials Engineering, San Luis Obispo, CA 93407 USA

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### **Abstract**

*Equipping engineering students with the skills and knowledge required to be successful global engineers in the 21<sup>st</sup> century is one of the primary objectives of undergraduate educators. Enabling students to practice self-directed learning, to find solutions to design problems that are sustainable and to recognize that they are part of a global community are just a few of our educational goals. Self-directed learning can define an individual's ability to practice life-long learning. It places the responsibility on the individual to initiate and direct the learning process and can enable an individual to adapt to change. Project-based learning provides the contextual environment that makes learning exciting and relevant. It provides an opportunity for students to explore technical problems from a systems-level perspective and to develop an appreciation for the inter-connectedness of science and engineering principles. In Materials Engineering, the model of a tetrahedron is often invoked to illustrate the bottom-up connectivity of the fundamental principles associated with a material's processing, structure and properties, which must be optimized to reach a desired performance. In addition, a top-down tetrahedron can be envisioned with the need for sustainability guiding the balance between economic, societal and environmental factors, which also influence the choice of the optimum design solution for a project. For students to fully explore this paradigm, it is imperative that project-based learning experiences be integrated throughout their undergraduate education. This article will explore methodologies that we have adopted to implement project-based learning through our four year undergraduate curriculum. Significantly, our course evaluations indicate that students strongly feel that this is a better method for "learning" and believe that the projects provide a more realistic environment for applying the principles of engineering, science and mathematics towards solving practical problems.*

Keywords: Project-based learning, systems engineering, self-directed learning, service-learning, sustainability, teamwork, critical thinking

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## **Preparing Engineering Students for the 21<sup>st</sup> Century**

Undergraduate engineering educational curricula are facing a number of challenges including a rapid growth in what is perceived by the technical community to be a necessary foundation of knowledge, the realization that our workforce must be able to operate in a diverse global society and the recognition that the implementation of technology can have an enormous impact on the sustainability of our global resources. If our students are going to successfully function as professional engineers in the international corporate world of the 21<sup>st</sup> century, they must be equipped to be global engineers who are technically versatile (multi-disciplinary), able to solve problems from a systems-level perspective, effective communicators, function in diverse ethnic teams and demonstrate social responsibility. Accordingly, our undergraduate educational curricula must keep evolving in order to provide the proper learning environment for students to develop these characteristics.

In the United States, the National Academy of Engineering has underscored the need for these changes and has established a center to facilitate systematic reform of engineering education [1]. The Accreditation Board for Engineering and Technology has modified their accreditation criteria to place an emphasis on project-based learning (problem solving) and self-directed learning which supports life-long learning [2]. While there are a number of pathways that can be taken to accomplish curricula reform, a common theme is to emphasize the creative elements of engineering through the integration of project-based learning (PBL) experiences. A project, based on solving a technical design problem, gives students a contextual environment that makes learning relevant and focused. Solving the problem drives learning, rather than the traditional “teach by telling” lecture format. Learning is something that students must do and take ownership of (self-direct), rather than something that is done to them. Self-directed learners are better equipped to adapt to change and they possess the tools that are necessary to practice life-long learning. Significantly, it is our belief that project-based learning is most effective when integrated throughout the undergraduate curriculum. It should not just be a single experience, such as a capstone senior project, club sponsored activity or laboratory activity. Only by integrating project-based learning experiences throughout the undergraduate curriculum will we give students the opportunity to develop a mastery of the fundamentals of science, engineering and mathematics along with providing them with the contextual environment for developing the skills necessary to practice engineering such as project management, teamwork and effective communication.

### **What is Project-based Learning (PBL)?**

For an engineer in industry, a project is a sequence of tasks required to reach an objective. Typically, the objective is to design a device or process that has value to a customer (user). The project begins by defining a performance problem associated with an application and ends with a design solution. The problem drives the learning required to complete the project. Managing the project requires the engineer to demonstrate effective teamwork, clear communication and the ability to balance the social, economic and environmental

impacts of the project. Project-based learning is based on the practice of solving problems. The concept of problem-based learning was first developed in the medical field in the mid-1950's [3]. Medical schools used problem-based learning to replace the traditional lecture-based approaches to teaching anatomy, pharmacology and physiology. It has since been adopted in a variety of educational disciplines including Business, Education, Law and Engineering [4, 5, 6]. Traditionally, the educational process involves students first learning the fundamentals and then utilizing "total recall" to apply these facts to solve a problem; learning objectives are set by the instructor and principles are presented to the students through lectures. Assignments are given to reinforce the application of the concepts, but often students merely "learn" what is necessary to pass the test or "repeat-back" information to satisfy the instructor. In contrast, the PBL approach employs a problem as the driving force for learning the fundamental principles that are required to find a solution. Moreover, this approach provides a context that makes learning the fundamentals more relevant and, hence, results in better retention by students [7, 8]. For clarity, we view problem-based learning as pertaining to the development of knowledge based on the fundamental principles of science and mathematics and project-based learning to include mastering the engineering skills required to implement a design solution.

### **Implementing Project-based Learning**

Each PBL experience begins with the students being introduced to a set of user defined performance requirements [9]. It is imperative that a clear and concise design objective statement be formulated. From this statement a list of functional requirements (what the design must do) can be derived and potential conceptual design solutions (how the requirements are achieved) are identified. Potential design solutions are analyzed from a systems level perspective, which explores the inter-relationships of components, including how they interact with each other and their operating environment. Next, a detailed design solution is developed and specifications are established that will enable the design to be fabricated and tested. A prototype of the design solution is built and tested to validate if it meet the original performance requirements. A project plan is usually developed to guide students through the process, support teamwork, focus communication and evaluate if the economic objectives of the project are being achieved. Throughout this process the students are challenged to learn how to *work in teams* and to practice *systems level thinking* when integrating technologies. Students are also challenged to recognize that their designs must both solve technical problems as well as make a contribution to society, a concept we refer to as *the dual tetrahedron approach*.

#### Teamwork

PBL activities can be individually oriented, requiring students to be self-directed, or they can be team-based requiring cooperative learning. It has been shown, however, that team-based learning is a better method [10]. Peter Senge states that the core disciplines necessary to build a learning organization are personal mastery, mental models, team learning, shared vision and systems thinking [11]. He defines team learning as the process of aligning and developing the capacity of a team to create the results its members truly desire. It also builds on personal mastery, for talented teams are made up of talented individuals. Team

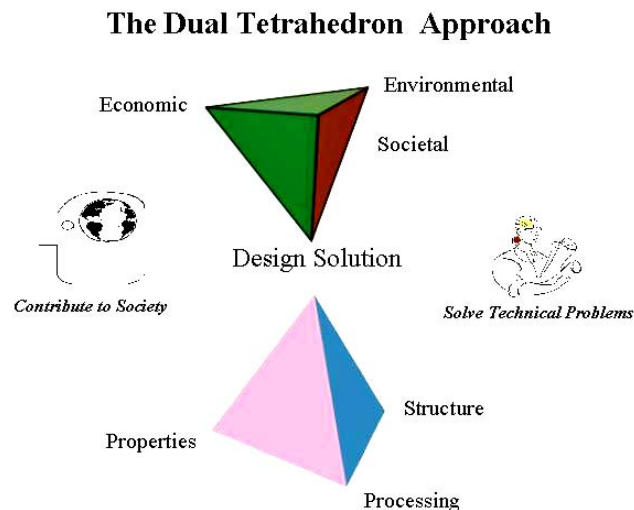
learning is vital because teams, not individuals, are the fundamental learning unit in corporations today. Organizations cannot succeed unless team members can learn from each other. Teams transform their collective thinking; they learn to mobilize their energies and actions to achieve common goals and, thereby, draw forth an intelligence and ability greater than the sum of the individual members' talents.

### Systems Thinking

Systems thinking emphasizes seeing the whole and establishing a framework for seeing inter-relationships rather than just individual components. It requires seeing patterns of change rather than static conditions and many have identified the need for taking this type of approach when developing design solutions [12, 13]. A systems approach to design involves learning that complex systems cannot be optimized by simply optimizing individual sub-systems; it requires an in-depth knowledge of how the sub-systems interact with each other [14]. It takes place after a conceptual design is established, but before the detailed design solution is completed. It requires students to evaluate the architecture of the design solution and explore the inter-relationships of its functional requirements and the operating environment.

### The Dual Tetrahedron Approach

In materials engineering, achieving the right performance in your design involves selecting the right balance between a material's properties, structure and processing. The tetrahedron has often been used to symbolize this bottoms-up process for solving technical problems. One can also visualize a top-down tetrahedron which represents the process of balancing economic, environmental and social factors when selecting the right solution to a design problem, as shown in Figure 1. The two pyramids (or dual-tetrahedrons) converge at the design solution and the process of optimizing this convergence requires critical thinking and self-directed learning.



**Figure 1. The dual tetrahedron represents the balancing of technical knowledge, economic, environmental and social factors when developing a design solution.**

Leaders in engineering education have recognized for a long time that engineering and science curricula have too many courses where problems are presented to the students as a tidy application of a few technical principles, whereas, in industry, most problems are multi-disciplinary, open-ended in nature and often have economic constraints [15, 16, 17]. William Wolf, President of the National Engineering Academy, has suggested that students should be given design problems with a limited number of constraints, then ask the students to articulate their own unique design solutions [18]. This process requires a student to carefully consider several conceptual design solutions and identify the impacts that their decisions might have on non-technical factors such as market positions, product profitability and environmental impact. Learning to recognize and balance the economic, environmental and social impacts associated with technical decisions will enable students to recognize that the primary role of being an engineer is to serve humanity.

### Key Elements of PBL Activities

A summary of the key elements that we have found to support the implementation of PBL follows:

1. Establish team dynamics and the role of the instructor. Ideally, teams should be in the three-to-six person range and the teams should be composed of students with a breadth of skills and backgrounds. For example, it is beneficial if each team has a member who is experienced in generating technical drawings (CAD) and relevant machining processes (mill, lathe, rapid-prototyping, etc.). Team building exercises should be utilized to facilitate the development of trust and communication within the team. It is imperative to let the students know up front that the role of the instructor is to challenge the learner to think rather than tell the learner what to do. The instructor should serve as a coach or facilitator to the teams. Students and faculty often fall back into the Socratic traditional role, where the teacher has all of the “right” answers and the learner must guess or determine through logical questioning which is the correct answer. Instructors must diligently work to avoid this approach.
2. Clearly identify the design problem and make sure students develop enough background knowledge to understand the application. Study the problem from a system or holistic perspective and identify the inputs and outputs of the design solution. Frame the problem carefully by identifying all of the relevant performance requirements and design constraints.
3. Detail the parameters necessary to solve the problem along with relevant tolerances. It is not uncommon for students to wind-up solving the wrong problem or developing a solution that exceeds the performance requirements. Neither of these results is desirable.
4. Encourage students to brainstorm with teammates and formulate ideas or hypotheses for conceptual solutions to the design problem before they settle on a final design solution. This provides an opportunity to reflect and discuss ideas with teammates and promotes teamwork. Identify the integration of technology required

- to solve the problem and list known relevant facts. Identify and prioritize topics that need to be researched in order to solve the problem.
5. Develop an action plan and utilize project management techniques like Gantt charts to track the progress of the design project. These steps will help to prioritize tasks for each member of the team and identify the critical path for the project. Establish milestones, such as design reviews, along with an overall time-line for the project. Design reviews are often utilized to assess the progress of the team and identify areas where the facilitator (instructor) needs to provide guidance to the team.
  6. Implement the action plan and fabricate a prototype of the design solution. It is imperative that each team identifies and completes the tests required to validate that the prototype meets all of the functional requirements. All test results should be discussed within the team and any areas that need further exploration must be identified and investigated. Each member of the team should be held accountable to the results and conclusions derived from the data collected.
  7. Summarize the results in both written and oral reports. Many times the design solution does not fulfill all of the problem's performance requirements, but there is great value in learning from mistakes and it is not at all uncommon for a team's "first" design solution to not meet all of the targeted performance objectives. It is important for students to recognize that there is not always a single "right" answer and that ill-structured problems can often have multiple solutions. Teams should be encouraged to communicate their results to the entire class and, hence, allow other students to learn from their efforts.

### Walking the Talk

Following these recommendations, we are endeavoring to integrate project-based learning experiences throughout a typical four year undergraduate engineering curriculum. Some activities span a few weeks, some an entire 10-week quarter, while a few extend throughout an entire academic year. Clearly a balance must be maintained between traditional lecture, laboratory and project-based learning activities; however, the majority of our courses are adopting a project-based format and we are carefully assessing the progress of our students towards developing the characteristics we have identified as essential for success in the 21<sup>st</sup> century. To help guide this process, each year in our curriculum has an area of emphasis: *first year* - the inter-relationship of science, engineering and math, *second year* – designing for sustainability, *third year* – a system's approach to engineering and *fourth year* – balancing depth and breadth. The following sections will summarize some of the PBL activities that we have adopted to support these themes.

### **The Freshman Experience: Inter-relationship of Science, Engineering & Math**

During their first year, students participate in a year-long project that focuses on helping them to synthesize principles from their technical support courses in mathematics, chemistry and physics towards solving applied engineering problems such as the design of a solar-based hot water heater or an emergency water purification system. The solar hot water and water purification systems are designed to meet the needs of local rural residents of San Luis Obispo County which provides a service-learning element to our curriculum and gives students a chance to see how their efforts can positively impact their local community. Additionally, students have an opportunity to develop an appreciation for the role of technology in improving society. The students design, build, test and install the systems for the rural county residents while third and fourth year students serve as project managers on the design teams. These projects provide students with a frame of reference that helps them to develop an appreciation for the relevance of the principles of science and mathematics, which are being conveyed in their first year technical support classes, for solving applied engineering problems.

### **The Sophomore Experience: Designing for Sustainability**

During the second year, students are challenged with two project-based activities. One involves evaluating the interconnectivity of engineering, marketing and operations roles and the second explores the impact that material selection can have on a product's life cycle. Students form product development teams and take on the marketing, design and manufacturing roles as they evaluate the viability of a commercially available product. They perform a life-cycle analysis on the commercial product and assess the environmental footprint of the materials utilized in the product's design. Particular attention is paid to sustainability issues such as the potential for recycling or design of the product for reuse along with the twelve principles of green engineering [19]. Product themes have included renewable energy devices along with products that integrate nanomaterials or smart materials into their design [20, 21]. Each team gives an oral presentation based on the commercial product that they have evaluated and their presentation is assessed by the instructor using a standard grading rubric. Students are evaluated for their individual performance as well as the team as a whole. Each student can invest stock (each student receives 100-shares) in the team(s) that he/she deems should perform the highest according to the grading rubric. A portion of each student's individual grade is tied to their investment; stock investments are paid-out as a multiple of the number of shares invested times that team's score as given by the instructor. This rewards students for taking the time to critically evaluate all of the team presentations and honestly invest in the team(s) that performed at the highest level. It has proven to be a particularly effective method for obtaining honest peer evaluations.

## **The Junior Experience: A System's Approach to Engineering**

There are five projects planned to be completed across the entire junior year. The emphasis is placed on taking a system's level approach when developing a design solution for these projects. The projects will be based on metallurgical, electronic, amorphous, structural and hybrid materials systems. The goal is to integrate fundamentals covering thermodynamics, kinetics, electrical, optical and mechanical properties of materials into the design solutions. To date, only the first two projects (metallurgical and electronic materials systems) have been completed which involve the casting of a metallic personal artifact that represents the values of the engineering department at Cal Poly and the development of a light measurement system for characterizing optical filters.

The casting project challenged the students to examine the inter-relationships among an alloy material's structure, processing and properties. For example, by explaining and predicting the microstructural changes that occur as a result of thermal processing. Then connecting this to measured hardness values for the cast objects. This project involved the use of 3D-conceptual modeling software and rapid prototyping techniques to design and fabricate a mold. Students then analyzed the impact that the casting process would have on the surface finish and determined the appropriate tolerances for the dimensions of the final object.

The light measurement system project required students to optimize their design to achieve a light throughput that would produce an optimum signal to noise ratio at the detector. The student teams designed and fabricated a measurement system that would transfer light from a source through optical fibers to a sample holder, collimate the light and send it through the sample filter; the light was then collected and sent via an optical fiber to a spectrometer for wavelength separation and detection by an array of photodiodes. The performance of each component had to be carefully optimized in order to achieve the user's defined precision and accuracy for characterizing the optical filter's performance. Electrical, optical and mechanical components were integrated together as system and the impact of design specifications on fabrication costs were carefully evaluated. A work breakdown structure was developed for the project and each team utilized a Gantt chart to monitor their progress and manage the assignment of tasks between different team members.

These projects required students to develop self-directed learning skills in order to solve the many design problems that they faced. The progressive development of self-directed learning skills throughout the curriculum is a key metric that can indicate the effectiveness of our PBL pedagogy. A self-rating assessment technique was employed to track the development of the students and the results will be discussed in more detail later in this article.

## **The Senior Experience: Balancing Depth & Breadth**

During their fourth year students take advanced topics courses with design projects combined with more traditional mini-lectures. These courses cover topics such as failure

analysis, corrosion, joining, microfabrication, microsystems, chemical analysis, nanotechnology, biomaterials, tribology, etc. Each course explores the principles behind engineering in greater technical depth and students can select the ones that enable them to broaden their knowledge in a field that fits their professional career objectives.

For example, in the microfabrication course, a class of twelve students is separated into four teams that must work together to complete all forty-seven process steps required to fabricate and test microelectronic PMOS transistor devices. The entire class works together as a mini-fabrication plant and processes one lot of twenty-five silicon wafers. The objective is to achieve a high yield of functioning transistors and each process step must be completed on time in order for the class to reach its objective by the end of the quarter. Each student writes a yield assessment report at the end of the quarter; all of the teams must pull together all of their process control data and identify any sources of yield loss for the entire manufacturing process. In parallel with the microfabrication process, two mini-lectures (total of three hours) are held each week, which allow students to explore each of the processing steps in greater depth. Students are challenged to demonstrate a mastery of the principles of science, mathematics and engineering and must apply critical thinking skills to solve the more challenging yield analysis problems.

### **Assessing Student Performance**

Throughout all of these PBL activities we have tried to maintain a careful balance between assessing the teams' and the individuals' performance when assigning grades. Students are given the opportunity, within a range set by the instructor, to select what portion of their grade will be tied to the teams versus the individuals performance (individual/team performance ratio). This gives students a sense of empowerment in the evaluation process and encourages accountability of each individual student to the team. Projects are supplemented with reading assignments and discussion questions that guide students through the self-directed learning process. Quizzes are periodically given based on the reading assignments and they must be completed individually and collectively as a team. The quiz grades are then determined based on the agreed upon individual/team performance ratio. Typically, there are no formal exams in the PBL activities. Written reports serve as the opportunity for students to demonstrate their individual capabilities and team oral reports reflect their ability to function effectively as a team. Techniques such as the stock investment plan, as described for the sophomore experience, encourages peer participation in the assessment process.

### **Assessing the Pedagogy**

Most of our assessments to date have focused on the freshman experience, which was a radical change from our traditional introduction to engineering course. For the freshman-level design activity, we assessed the effectiveness of the project-based learning experience by looking at changes in student attitudes: 1) about the engineering profession and 2) about their role in the learning process (self-directed learning). The specific learning objectives

and the performance benchmarks related to these two attitudes are itemized in Table 1. These objectives relate to the affective valuation level within the Bloom/Karthwohl hierarchy [22].

Objectives	Performance Benchmarks		
	<i>Low End Anchor</i>	<i>Mid-Point</i>	<i>High End Anchor</i>
Discusses the meaning of global and societal issues in relation to engineering BK Level-7	States global issues that impact society; states that the role of the engineering profession is to improve the health, safety and welfare of society	Articulates ways in which an engineer can overcome global challenges and improve health, safety and welfare of society; describes the link between public policy, technology and society's health, safety and welfare.	Identifies the need for disciplines outside of engineering in solving global challenges (lists specific disciplines); maps the interconnected relationships of poverty, environment, technology, gender equity, innovation, sustainable development in a causal loop diagram
Challenges oneself to learn what one needs BK Level-7	Identifies the gaps in one's knowledge	Researches the needed information	Fills the gap of knowledge as a result of the research by explaining the information in their own terms

**Bloom/Karthwohl Levels (1-7)**

1-Knowledge, 2-Comprehension, 3-Application, 4-Analysis, 5-Synthesis, 6-Evaluation, 7-Valuation (affective), 8-Psychomotor

**Table 1. Performance rubric for learning objectives related to student attitudes regarding the engineering profession and their role in the learning process.**

Significantly, the assessments indicate that all of the individual students in the freshman experience have achieved the *Mid-Point* performance benchmark for both objectives, as described in Table 1. In addition, each of the teams have demonstrated the *High End Anchor* performance benchmark for the second objective: “challenges oneself to learn what one needs.”

The main objective of our course evaluation process was to determine how and why student beliefs about the professional role of engineers changed through their PBL experience. Information was requested from all students, through an “on-line interview” process. The process began with a set of survey questions that were sent directly to all students by the evaluator (not the instructor) via email. As each student responded to the initial set of questions, the evaluator sent that student additional rounds of individualized questions, as needed, to probe for additional detail and to clarify the meaning of any vague or incomplete responses. Responses to the initial set of survey questions were received

from 24 of the 27 students enrolled in the freshman course yielding an eighty-nine percent response rate.

Overall, the freshman PBL experience had a significant impact on students’ mental models regarding the types of knowledge and skills that they believed they would need to develop in order to become successful engineers. Seventy-five percent of the students indicated that at least one specific aspect of their mental model had changed as a direct result of their participation in the course. Most notable among these was an increased understanding of the complexity of problems that an engineer is likely to encounter, and a corresponding emphasis on the skill of structuring complex problems so that many factors could be taken into account while solving them. Students also placed increased importance on teamwork and communication skills, an understanding of sustainability issues and the habit of paying attention to detail. Several factors within the design project were cited as causing students to change their opinions. The project was largely self-directed and viewed by students as painfully vague and unstructured. The “realness” of the project was the saving grace for most students who at times felt totally overwhelmed. But, they felt that it was worth it to have experienced what “real engineers” have to deal with on a daily basis. In addition, students were strongly influenced by the opportunities that they had to receive concrete feedback on their work during design reviews, both from the upperclassmen who served as their project managers and from specific instances in which they were forced to deal with problems that arose from mistakes in their own work, such as errors in calculations and blueprints.

The first question on the evaluation survey was an open-ended question regarding student impressions of the most important types of knowledge/skills that a person would need to develop in order to become a good engineer. A summary of all of the knowledge and skill areas mentioned in the student’s responses is presented in Table 2.

<b>Responses</b>	<b># of students</b>
Creative problem solving/design	18/24
Ethics	10/24
Communication skills	6/24
Basic knowledge of math and science concepts, and computer skills.	5/24
Teamwork skills	4/24
Resourcefulness	3/24
Perseverance	3/24

The most popular response to this question, mentioned by eighteen different students, was that engineers needed to have excellent problem solving skills. They must be able to successfully deal with unexpected difficulties, troubleshoot faulty or broken designs and use an analytic process to generate new solutions to complex and often ill-defined

problems. The second most common response to this question, mentioned by ten different students, was that engineers need to have a strong sense of ethics. They must pay attention to detail in order to foresee and avert any possible negative repercussions that their design decisions might have on people, the economy or the environment. Six students felt that communication skills would be very important to engineers not only when communicating design details to other members of the design team, but also when attempting to convince others and presenting design solutions to clients and other stakeholders. Five students felt that the most important knowledge and skills for professional engineers to have were content knowledge in science and mathematics, and an ability to operate specific types of machinery, such as CAD systems and scientific equipment. Four students cited teamwork as one of the most critical skill sets an engineer could acquire. In particular, these students emphasized the need for individuals to pitch in as necessary and the need for team leaders to know how to motivate others to do the same. The remaining two skills that students felt would be of vital importance for engineers were resourcefulness and perseverance.

The second question asked students to describe the ways in which their opinions about the knowledge and skills needed by good engineers had changed over the course of the freshman PBL experience. A complete summary of the student's responses to this question is shown in Table 3.

<b>Table 3: How my opinion has changed since the start of the year.</b>	
<b>Responses</b>	<b># of students</b>
Better understanding of the complexity of problem solving	8/24
No change; class reinforced prior beliefs	6/24
Increased importance placed on communication skills	3/24
Increased importance placed on sustainability	3/24
Emphasis shifted from rigorous theory to creative problem solving	3/24
Increased emphasis on math/number crunching	1/24
Decreased emphasis on math/number crunching	1/24
Decreased emphasis on tinkering and physical construction	1/24
Increased importance of teamwork vs. individual accomplishment	1/24
Increased importance of attention to detail	1/24

Among students who reported a change in opinion about the nature of engineering as a profession, eight students reported that, although they had known that engineers were “problem solvers,” their experience in the freshman-design course had helped them to understand just how complex an engineering problem can be. In addition to greater complexity, three students indicated that they had expected most of engineering to be more theory-oriented than the hands-on, creative design process they had experienced in this class. Three students also indicated that the course helped them understand the importance of communication skills in engineering and three others said that the courses had made them realize how important sustainability was to the engineering profession.

The third question probed students to determine what aspects of the course had affected their opinions about engineering. Their results are summarized in Table 4.

<b>Responses</b>	<b># of students</b>
Having to solve a series of vague, unstructured, real-world problems	10/24
Working in groups to accomplish real goals	5/24
Working with real clients	5/24
Design reviews/presentations	4/24
Coping with problems that arose due to miscommunication	3/24
Calculations that were needed to ensure our design could be built	2/24
Professor's emphasis on sustainability	2/24
Speakers' presentations on sustainability	2/24
Nothing – had to go outside MATE to find out what MATEs do	2/24
Help and advice from upperclassman project managers	1/24
Readings on sustainability	1/24

The factor that had the most impact on students' opinions regarding the knowledge and skills that they would need as engineers was the experience of having to solve a series of vague, unstructured, real-world problems. It may have been uncomfortable, but the vagueness of the problems was one of the things that made them learn. Another area that affected their opinion was the process of completing design reviews. Four students mentioned that these had been one of the most influential aspects of the course, because the reviews held them accountable for the work while providing crucial feedback on what they were doing right and wrong in their approach to solving their design problems.

The majority of the students who took the freshman course sequence felt that it had done a particularly good job of teaching them about global and societal issues that relate to engineering, and in particular, the importance of sustainability in design. The specific aspects that helped students with this objective are summarized in Table 5.

<b>Table 5: Aspects of the course that helped me learn to discuss the meaning of global and societal issues in relation to engineering.</b>	
<b>Responses</b>	<b># of students</b>
Assigned readings in Scientific American	16/24
Presentations by outside speakers on Green Chemistry/Engineering	7/24
Group discussions of readings, in class	6/24
Video on sustainability (“Cradle to Cradle”)	3/24
“Reflections” writing assignments	2/24
Field trip to the dump	1/24
Quizzes	1/24

The most commonly cited factor contributing to this learning was the series of Scientific American articles that students said served as a supplementary “textbook” for the course [23]. Several students also pointed out the importance of the outside speakers’ presentations on Green Chemistry/Engineering [19]. They also cited classroom discussions of the readings, which helped them to better understand the content. In a few cases, the study of these topics is even cited as a specific reason to select materials engineering as a major.

The specific aspects of the course that encouraged students to challenge themselves to learn what they needed to know (self-directed learning) are summarized in Table 6.

<b>Table 6: Aspects of the course that helped me learn to challenge myself to learn what I need.</b>	
<b>Responses</b>	<b># of students</b>
Vagueness of instructions for class projects (for good and ill)	20/24
Design reviews/presentations (fear of humiliation)	3/24
Competition with peers who seemed to know more	2/24

For most students the process seemed like trial by fire. Even though students expressed frustration with what they perceived to be vague assignments, in the end their struggles seemed to yield a deeper level of understanding. The transition from the extremely guided learning environment of high school to complete self-directed learning in this freshman-series course was extremely frustrating for many students. We realize that there needs to be a more gentle transition to prevent the students from being overwhelmed.

Overall, the integration of PBL throughout our curriculum has resulted in an increase in the retention of students between the first and second years to about 65%. Traditionally, this number has been less than 50%. We have also seen an increase in the number of students transferring into Materials Engineering from other majors and the number of cross-disciplinary senior projects has increased. In addition, our rate for on-time completion of senior design projects has risen to 100% for the past several years, which indicates that our students are developing a mastery of the skills required for successful completion of an engineering project.

## **Conclusions**

There are a number of challenges that we have experienced while trying to implement PBL activities. Assessment is difficult particularly at the individual level. How do we apply quantitative measurements to this learning process and assign grades? How do we know if we are achieving the right balance between the depth and breadth of the knowledge that our students will need to be successful? What is the measure of success of our students? These activities are also very resource intensive both in faculty time and design materials. Funding the projects can be difficult although we are seeing an increase in corporate partnerships and donations specifically to support PBL activities. The PBL process requires students to be very self-directed in their learning and to take “ownership” of their own education. Confident students are able to do this but many students do not know how to find and distill the information down to the principles required to solve the problem. Care must be taken to select projects that do not present too complex a learning environment. If too many principles must be assimilated at once, students can become frustrated which can dilute the learning experience. Projects must be based on problems with achievable solutions. Students also need to see the relevance of the problem. If the project is not “interesting” then students will not put as much effort into finding a solution. It is challenging to come up with projects that capture the interests and motivation of the entire class.

Project-based learning can be an extremely effective method that empowers students to learn both the fundamental principles of science and to develop an understanding of how they are utilized in applied engineering to solve design problems. It also provides them an opportunity to see designs from a systems perspective and develop an appreciation for technical challenges in the context of global societal, economic and environmental requirements. While the value of PBL experiences seems clear, the implementation remains a challenging task for both faculty and students. Hopefully, some of the experiences shared in this paper will support and encourage others to facilitate the integration of these activities throughout their undergraduate engineering curriculum.

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