AC 2007-2550: FIRST-YEAR EXPERIENCE AND BEYOND: USING THE ENGINEERING DESIGN PROCESS TO SUPPORT LEARNING AND ENGINEERING SKILL DEVELOPMENT

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First-year Experience and Beyond: Using the Engineering Design Process to Support Learning and Engineering Skill Development

Abstract

First-year engineering programs increasingly introduce a focus on the engineering design process, responding in part to accreditation needs and industry advice. Yet too often these introductions to the design process are one or two semesters only, resulting in students not having time to either complete genuine design projects or not absorbing the process sufficiently to be able to apply throughout their academic years. This paper describes a service-learning project that began in a one-semester introductory course, but that continued over three semesters.

Students from a variety of majors in the College of Engineering and Applied Sciences (CEAS) at Western Michigan University, enrolled in a first-year Introduction to Engineering class in Fall 2005, worked in teams to design a working prototype of a demonstration kit for a local high school science teacher. The demonstration kit was intended to safely teach x-ray diffraction of a single crystalline solid (by substituting lasers instead of using harmful x-rays) and to allow the high school teacher to demonstrate the mathematical concepts of 2-, 3-, and 4-fold rotational symmetry. In completing these designs, the students closely followed and applied the engineering design process. In the second semester, a group of three of the original 30 students re-evaluated, re-designed, and fabricated their prototypes from the previous semester.

Through this first-year project, these students were responsible for the entire cycle of engineering design, from concept through implementation – a rare opportunity. This paper explores not only the success of one student design project stemming from applying the engineering design process in a first-year engineering program, but also presents from our experience ways in which student learning and development can be enhanced in the first year and continued and augmented beyond the first-year experience.

Introduction and Project Objectives

In the fall semester of 2005, 30 students enrolled in a three-credit (two hours lecture; two hours laboratory per week) university course for first-year engineering students (ENGR 1010 "Introduction to Engineering and Technology") were instructed to complete a guided design project, solving a real problem for a real "customer." Their charge was to create an instructional device to simulate x-ray diffraction of single crystals. Working with a high school physics teacher (their "customer"), teams of first-year engineering students used the engineering design process to create a device that effectively simulated the phenomenon of x-ray diffraction. X-ray diffraction is the scattering of x-rays by atoms of a crystal into a crystalline lattice pattern. The teacher wanted his students to be able to see and understand how Bragg's Law, a mathematical definition explaining x-ray diffraction, works.

In 1913, Sir W.H. Bragg and his son, W.L. Bragg, derived an equation that validated the fact that real particles exist at the atomic scale.[1, 2] The Bragg's Law equation can be manipulated to show a direct relationship of the wavelength of the x-ray to the lattice parameter of the object and wavelength of laser and commercially available diffraction film, as shown below.

$$\frac{n\,\lambda_x = 2\,d_x \sin(\theta_x)}{n\,\lambda_l = 2\,d_l \sin(\theta_l)} \qquad \textbf{\textit{Equation 1}}$$

where *n* is the order of diffraction, and the subscript *x* represents x-ray and atoms and *l* represents laser and diffraction films.

$$\frac{\lambda_x = d_x}{\lambda_l = d_l} \qquad \textbf{\textit{Equation 2}}$$

Equation 2 shows the ratio of the wavelength of an x-ray (λ_x) to the distance the atoms are separated (d_x) is proportional to the wavelength of a laser (λ_l) to the distance separating the lines inscribed in a diffraction film.

Drawing from the teacher customer's experience that teaching concepts solely through reading assignments and lectures failed to provide either interest or relevance, he wanted an apparatus that would allow his students to learn this concept through hands-on experimentation. The task for the first-year engineering students was to represent x-ray diffraction using lasers but in a ratio that is mathematically equivalent to using actual x-rays.

The main project objective was to design a prototype or demonstration kit that could be used to teach high school students the physics and mathematics behind the theory of x-ray diffraction. To reach this goal, the teams of first-year engineering students implemented the engineering design process [3, 4] to formulate two demonstration kits, one a model for teacher use and the other a model for student use.

Applying the Engineering Design Process

Following the engineering design process, research about x-ray diffraction was first completed in order for the first-year engineering students to have a good grasp of the topic themselves. The entire class of 30 students first researched the physics of x-ray diffraction of a single crystalline solid and the concept of rotational symmetry of cubic crystals. Following consultation with the teacher customer and the university course instructor, the students generated an extensive list of constraints (project limitations) and criteria (goals for the end-result), an important aspect of the engineering design process.[3]

The common specifications for the two kits were as follows:

- **Constraints:**
  1. The design should illustrate a set of concepts of x-ray diffraction of a single crystal or one concept in multiple ways.
  2. The design must allow users to manipulate variables or to collect data.
  3. The design must address safety concerns of the end users and use only non-toxic materials.

4. The design must not cost more than $100 to produce.

- **Criteria:**
1. The design should have a device that allows the user to rotate the grating films.
2. The design should have pre-made slides.

Additional specifications particular to each demonstration kit were as follows:

- **Constraints for teacher kit:**
1. The design must be lightweight and portable.
2. The design must be able to project onto a wall thirty feet away and be visible to the entire classroom.
3. The design must be constructed from durable and accessible parts that, if broken, can be replaced easily.

- **Criteria for teacher kit:**
1. The design should use laser pointers as opposed to modules.
2. The design shouldn't have lasers and films that rotate on the same axis.
3. The design should use dual lasers, each with their own set of rotating films.
4. The design should feature lasers that are placed an optimal distance from the films.

- **Constraints for the student kit:**
1. The design must include a screen to see the scattered beam.
2. The design must use laser modules.
3. The design must not have any exposed wires.

- **Criteria for the student kit:**
1. The design should have the screen a distance of 5 inches from the slide.
2. The design should have a rigid housing.
3. The design should have compartments within itself to contain the slides.

Students then brainstormed ideas, synthesized possible solutions, and selected a final design that best met the design specifications and project constraints. The students also performed vendor research for the kit's components, mindful of the established project budget, and fabricated a proof-of-concept prototype. The high school physics teacher, acting as a customer, worked with the Western Michigan University course instructor to review and evaluate all of the demonstration kits from the eight teams of first-year engineering students, and the two best designs were selected for further development and refinement.

Design Beyond the First Semester

Here the introduction to the engineering design process for first-year engineering students would typically stop, and did for almost all the students in this class. However, a team of three students (who are the lead authors for this paper) continued the development and refinement of the best design as part of their enrollment in the one-credit (one hour recitation per week) ENGR 2020, "Service-Learning Engineering Design I," during the Spring 2006 semester. Using feedback from the teacher customer from the previous semester, the student team came up with new design ideas to better meet his needs. Two working prototypes were designed which incorporated some elements from several of the devices originally constructed for the ENGR 1010 course, as well as new features. One of the prototypes is specifically for the teacher to demonstrate the concepts of x-ray diffraction of single crystals to his students. The other prototype is designed for the students to experiment with and collect data on diffraction patterns. The engineering student team continued to work with the science teacher and incorporated his feedback to refine the two demonstration kits and create lesson plans that best suited his and his students' needs.

The team of first-year engineering students worked with a machinist to select materials and define the machining process that would be used to create the prototypes. One of the selection constraints for the final design included a maximum cost so that the kit was relatively inexpensive and would work within school budgets, so that it could effectively be used in classrooms to educate students using a hands-on method. After construction, the prototypes or demonstration kits were tested, evaluated, and further refined by experimentation with the teacher customer, as well as groups of his high school physics students. At this point, the engineering student team met on-site with the teacher customer and some of his students for informal testing and feedback.

In ENGR 3030 "Service-Learning Engineering Design II," during Fall 2006 (the third semester of the project), the team of students refined a lesson plan to use with the demonstration kits, including a short lecture, written pre- and post-surveys, written instructions, and an activity worksheet. In mid-December, 2006, in-class testing was conducted with three physics classes at two different high schools. Students gathered both quantitative and qualitative data on the high school students' use and learning resulting from use of the demonstration kits. Pre- and post-surveys of the high school students to document their level of understanding of concepts related to Bragg's Law and light diffraction, as well as observational techniques, were used to collect data. Finally, the collected data were analyzed to determine how to continue to improve the demonstration kits and their use. The use of feedback and testing to improve the kits illustrates the iterative nature of the engineering design process. Details on the classroom testing and data analysis are shown below.

Finalized Designs for the Demonstration Kits

Using the design constraints, criteria, and feedback from the high school teacher and faculty mentors in ENGR 2020 and 3030, the team of engineering students fabricated two demonstration kits.

Teacher Demonstration Kit

The design for the teacher's demonstration kit is made specifically for demonstration purposes rather than personal experimentation. Its main purpose is to introduce the theory and ideas expressed in Bragg's Law. The kit is designed to be projected onto a surface approximately 20-30 feet away.

The demonstration kit is made of wood and uses a red and green laser pointer, each with on/off switches. The wood has cutout slots that the lasers fit in so that they stay securely in place. There is another cutout slot that holds the square slides, or light diffraction grates. There are four slides or grates in total, and they are housed on the right side of the kit. Figure 1 shows the teacher demonstration kit.

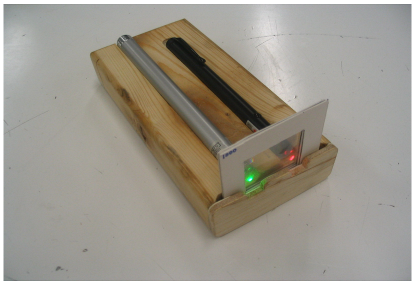

Figure 1. Teacher Demonstration Kit

Student Demonstration Kit

The student demonstration kit allows high school students to experiment with x-ray diffraction, with the goal of applying Bragg's Law. It features both a red and green laser module that points vertically downward through a diffraction grating film and onto a projection screen. The laser modules are contained in a rectangular casing so that the lasers are pointing in opposite directions. This is so that the module holder can be rotated 180˚ to switch from the red to the green laser and show the difference in the diffraction using the different laser wavelength.

A holder for the diffraction grating slides allows the students to rotate the slides through a circular motion to see that the crystals have rotational symmetry. The boxed base has a flat surface that the laser beam is diffracted onto and holds a piece of paper so that students can trace the diffracted dots of the laser and measure the distance between them. The base is hinged, and all parts can be disassembled and stored within. The base also has a rack that holds the five slides and has room for the teacher demonstration kit, a ruler, markers, and any other materials used in the lab, as shown in Figures 2 and 3.

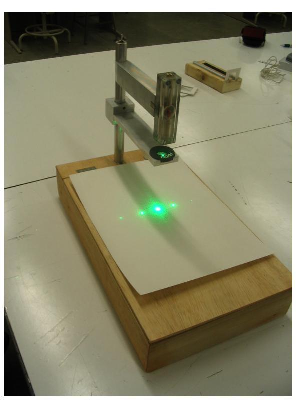

Figure 2. Student Demonstration Kit, Assembled

Figure 3. Student Demonstration Kit, Disassembled

Testing of Demonstration Kits

In April 2006, the engineering student group of three met with the high school physics teacher customer to discuss and evaluate the design prototypes. The teacher filled out a customer feedback form that had been prepared prior to the meeting. In general, he was impressed by the students' designs and thought they fully met the design specifications that were previously stated. Along with the positive feedback, he suggested that the team do in-class testing with associated activity worksheets before any further prototype production schedules were established.

To do in-class testing, the student group needed to construct a lesson plan. As previously stated, this lesson plan contained a short lecture, pre- and post-surveys, instructions, and a worksheet for the high school students to complete. The lecture described the project objectives and introduced Bragg's Law, the concept of x-ray diffraction, and rotational symmetry. The teacher demonstration kit was used to aid in conveying these ideas. The pre- and post-surveys had general questions in an attempt to compare the two surveys to determine if the students learned anything from the lesson. The worksheet to be used by the high school students went step-by-step through the manipulation of Bragg's Law, to show that using the lasers is directly related to using x-rays. The activity then required the students to record data using the demonstration kits, and to use that data to solve for unknown variables in the equation for Bragg's Law. The worksheets also had a few simple questions to determine if the students understand the idea of rotational symmetry. All of these materials were prepared with the advice of the high school teacher customer and the university faculty instructors.

In December 2006, the student team went to a local high school and tested the demonstration kits in the teacher customer's physics class. Although there were 24 students enrolled in the class, only 19 were able to participate due to time constraints. In order to expand the pool of students testing the kits, with the help of faculty advisors, the student team contacted a physics teacher from another nearby high school, and proposed their plan to him. He was interested in the project and invited the group to test the kits in two of his physics classes. At that site, the team collected 37 more sets of data. This second testing day went more smoothly because of greater time allotted to the testing, and the student team was also able to interact more with the students on a personal level.

Classroom Testing Results and Discussion

Qualitative, quantitative, and observational data were collected as part of the testing process in the three high school classrooms. Quantitative data were collected using the written pre- and post-surveys with the high school students. Qualitative comments were collected from written comments on the worksheets completed by students. Observations were recorded by the team of engineering students as the classroom presentation and testing were underway.

Quantitative results from the pre- and post-survey questions are compiled in Table 1. A 4-point Likert scale was used to determine the level of basic understanding amongst the high school students who participated in the testing. As shown in Table 1, the mean values compiled from the pre- and post-survey responses increased dramatically, in some cases by 60% or more (understanding lasers and x-ray diffraction).

Table 1. Results Compiled from Written Pre- and Post-Surveys

What is your basic understanding	Pre-Survey Mean* (1 to 4 scale)	Post-Survey Mean* (1 to 4 scale)
of lasers?	1.73	2.80
of x-rays?	1.91	2.78
of crystals?	1.57	2.40
on x-ray diffraction?	1.35	3.52
of wavelength?	2.46	3.88
	Pre-Survey Mean (0 = no; 1 = yes)	Post-Survey Mean (0 = no; 1 = yes)
Do you know what diffraction is?	0.38	0.98
Do you know what rotational symmetry is?	0.68	0.96
Have you worked with lasers in a classroom before?	0.18	0.76
Have you ever heard of Bragg's Law?	0.05	0.75
Are you interested in learning about x-ray diffraction?	0.66	0.75
* 56 respondents to pre-survey; 51 respondents to post-survey		

The second part of the written pre- and post-surveys collected "yes" and "no" student responses, with a "yes" response converted to a numerical score of 1, and a "no" response coded as a 0. From Table 1, most of the high school students had not previously been exposed to the concept of Bragg's Law (0.05 mean value). Table 1 also shows that in the opinion of the high school students, they have enhanced their knowledge about diffraction, Bragg's Law, and rotational symmetry, as the mean values are increased. In both the pre- and post-surveys, students seemed to be motivated to learn about x-ray diffraction regardless of the classroom testing exercise, as there was only a small increase in the mean value for that question (0.66 to 0.75). This is not unexpected, as students enrolled in a high school physics class should be interested in science or engineering topics, or else they would not have selected that course of study.

Qualitative comments from the high school students were collected from the "general comment" section of the written survey, or recorded by the team of engineering students during the classroom testing exercise. The high school students seemed to be very satisfied. In general, the team of engineering students received positive feedback, while many high school students expressed their gratitude for presenting a straight-forward explanation of a difficult concept. On a particular post-survey, one student wrote, "Fun; the worksheet was easy to understand, and help was readily available." Another said, "It was much more enjoyable doing the experiment than just lecturing on the idea."

Based on their own experiences with physics labs, one of the goals the team of engineering students had was to make the experiment easy to understand and follow, along with providing an effective teaching device. Overall, the team of engineering students felt that their lesson plan and demonstration kits illustrating Bragg's Law and diffraction concepts were successful, based on data and feedback gained during the classroom testing,

Based on the results of in-class testing, the engineering student team made the following recommendations for the kits and their use:

- The slide holders in the teacher demonstration kit be reconstructed so that they will show rotational symmetry.
- A stand could also be constructed for the teacher kit so that it will always be perpendicular to the projection screen.
- The instruction sheets may need minor adjustments, along with the pre- and post-surveys if any further testing needs to be completed.
- The worksheets used by the high school students need columns added to the table for recording data, and space to complete calculations.
- Finally, since there was limited time with the high school students, any teacher using the kit may want to go into further depth explaining x-rays, lasers, and x-ray and laser diffraction and their real-life functions prior to the hands-on experimentation.

As a result of the in-class testing and observations that were recorded, the engineering students realized several things. First, the students recognized their attempt to make this project straight-forward, understandable, and interesting was greatly appreciated. And second, the engineering students gained a greater appreciation for the effort and amount of work required of teaching faculty at both the high school and university level.

Development of Professional Skills

This team of first-year engineering students was able to comply with a request from a high school physics teacher for a teaching device to convey the concept of x-ray diffraction using lasers. The students used the engineering design process from start to finish to construct two working demonstration kit prototypes. These prototypes, now fully implemented and tested, have proven to successfully demonstrate the concepts and improve high school students' understanding of x-ray diffraction and Bragg's Law concepts.

Beyond the experience gained through the technical and engineering aspects of this project, students learned, applied, and refined a broad range of both engineering and professional skills. As novice engineers, the team realized that the engineering design process is not limited to a few designated courses in their curriculum, but has broad applications in everyday learning activities.

This group of three engineering students, new freshmen when the project began and unknown to each other, developed strong teamwork and interpersonal skills through using the engineering design process to solve a real problem for a real customer. Establishing and following a project plan was crucial to keep the project progressing, and students refined their time and project management skills as they gained increasing ownership for the project. Interacting with their teacher customer taught them tact, good listening skills, and professional e-mail practices.

Project documentation is an integral part of the engineering design process. The students kept individual and group project notebooks, which were discussed and periodically reviewed by faculty. The student team also provided numerous written progress reports, as well as formal final reports at the end of each of the three semesters. Oral presentations throughout the process included informal updates to faculty advisors, structured progress reports to classmates and faculty, on-site updates to the teacher customer, and, again, formal oral presentations at the end of each semester. All of this documentation and oral presenting was discussed and modeled by faculty advisors. In addition to the required and graded documentation and presentations on their design project, these students have presented their work at regional (and now national) conferences and have their posters prominently displayed in the engineering building on campus.

The professional, interpersonal, and leadership skills gained in part through this project have been recognized, and put to use. As has been seen in other service-learning projects, completing a service-learning activity where they created teaching materials for younger students in the community helped develop their own ability to support others' learning. [5, 6] In their second year of college, these three engineering students now act as mentors to students enrolled in the three engineering design classes this group has completed, and as tutors for at-risk first-year students in the engineering college.

Already recruiters have expressed interest based on inclusion of the project on students' resumes. Thus this first-year experience has led to development of other critical skills, including lifelong learning, communication, and general professional growth, very early in these students' academic lives.

Recommendations for First-Year Programs

Every first-year program is different. In this case, a student project that developed out of a first semester introduction to engineering design course succeeded beyond that course because of a combination of project opportunities and student interest generated in that course. Beginning or nurturing community connections is recommended as a means of providing opportunities for experiential learning for even first-year students. In this case, and many others, local K-12 teachers are usually eager for college faculty and students to provide materials and activities to support their own teaching. [7, 8] The high school physics teacher involved in this project has now come back to Western Michigan's CEAS requesting further projects. Local Boys' and Girls' clubs, YMCA and YWCA groups, and not-for-profit organizations such as Goodwill Industries and Habitat for Humanity often seek engineering students and faculty to support their own programs.

Motivating first-year students to continue projects beyond that first class may be more difficult. Engineering students, and especially freshmen, often feel overwhelmed and overworked. What worked in this situation was having a curriculum offering one-credit courses in which students could continue projects, and a core of faculty working with each other to support such opportunities. If the curricula do not permit this structure, independent study or special topics courses could be used and should be supported. Perhaps more important, faculty able to make engineering design relevant and accessible to new students should find ways to interact with each other across the engineering college or the university. And finally, first-year engineering students come to college full of energy and a vague desire to make things better. The students themselves need to be gently nudged to be active, rather than passive, participants in such activities as described here. It did not take much pushing to motivate and inspire this student team to make a difference.

The Last Word: Students' Perceptions on the Value of Their First-year Experience

Since many engineering students do not have the opportunity to continue or even complete projects or lessons that begin in their first year of college, we feel very privileged to have had this opportunity. Our student team of three was able to implement the engineering design process in our first year of engineering college, something many students are not given the chance to do until their senior year. To manage a project that has lasted over three semesters so far has undoubtedly been challenging, yet very gratifying. One aspect of this project that we are thankful for is the opportunity to fully learn about this concept and to actually work in the community to teach others. To work so hard to create a device that teaches a concept that we hardly understood in the beginning, and to see others learning from it in the end, is a truly rewarding experience. Educationally, we were able to completely understand the concepts and theories of x-ray diffraction that we are attempting to teach to younger students. Most important, we learned the engineering design process through personal experience, something that we will be able to use throughout the remainder of our engineering careers.

We have gained a great amount of professional, educational, and personal development from this project. Professionally, we have developed oral, written, and visual communication skills, and have made contact with some of the most prestigious names in the engineering community. We have presented our preliminary design at a regional engineering conference in April 2006, where we were the only freshmen among many seniors and graduate students. We also learned the value of professional e-mail practices with clients and practicing professionals, a skill often ignored by students and not well taught in the academic world. We thus have gained important additions to our résumés – information already noticed by recruiters. We also gained a greater respect for instructors, teachers, and professors, as we now realize how much work and dedication is required to teach students every day. On a personal level, we were each able to hone our newly developed skills to become mentors for the students in the current ENGR 1010 class, using our free time to assist the new freshmen with their design projects. We were even considered mentors in our ENGR 3030 class, although we were the youngest students in the course. All together, our first-year experience went, and, we believe, will continue to reach, far beyond the first year of college.

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