Work in Progress: Building a Functional Cardiograph Over Four Semesters

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Dr. Gail Baura is a Professor and Director of Engineering Science at Loyola University Chicago. While creating the curriculum for this new program, she embedded multi-semester projects to increase student engagement and performance. Previously, she was a Professor of Medical Devices at Keck Graduate Institute of Applied Life Sciences, which is one of the Claremont Colleges. She received her BS Electrical Engineering degree from Loyola Marymount University, her MS Electrical Engineering and MS Biomedical Engineering degrees from Drexel University, and her PhD Bioengineering degree from the University of Washington. Between her graduate degrees, she worked as a loop transmission systems engineer at AT&T Bell Laboratories. She then spent 13 years in the medical device industry conducting medical device research and managing research and product development at several companies. In her last industry position, Dr. Baura was Vice President, Research and Chief Scientist at CardioDynamics.

Dr. Leanne Kallemeyn, Loyola University Chicago

Leanne Kallemeyn, Ph.D., is an Associate Professor in Research Methodologies at Loyola University Chicago. She teaches graduate-level courses in program evaluation, qualitative research methods, and mixed methods. She has been the PI on seven major evaluation projects that ranged from one to five years in length. Her scholarship focuses on practitioners’ data use and evaluation capacity building within non-profits through coaching. She received a Bachelors in Psychology from Calvin College, and a PhD in Educational Psychology from the University of Illinois, Urbana-Champaign.

Mr. Noe Arroyo

I am a mechanical engineer in the medical device industry.

Dr. Vincent C.F. Chen, Loyola University Chicago

Dr. Vincent Chen is an Assistant Professor of Biomedical Engineering with expertise in neuromodulation and rehabilitation engineering. He received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from National Taiwan University, and pursued a career in the tech industry while working on his graduate degrees. Before joining Loyola University Chicago, he worked as a Postdoctoral Research Fellow at Harvard Medical School and conducted clinical research at the Neuromodulation Center of Spaulding Rehabilitation Hospital in Boston. His current research focuses on quantifying the extent of neuroplasticity induced by the application of brain and peripheral nerve stimulation.

Mr. Allan Beale

I have a BSEE from the University of Maryland, 1967 thus I have 50 years experience divided between 3 different fields: Aerospace, Computer and Medical. For these fields, the work was mostly analog and digital design. Software was required for all the medical products which was performed by others who had to meet my design requirements. The medical products involved designing microvolt level analog circuits, ADCs, discrete digital, microprocessors and PGA digital circuits, for testing to design specifications and approving to FDA, CE, UL, etc., specifications for heart pacemakers, neuro-stimulators and other medical products.
WORK-IN-PROGRESS: Building a Functional Cardiograph
Over Four Semesters

Abstract

In this paper, we present the first semester of a four-semester design project to build a functional cardiograph that estimates heart rate and respiratory rate. This set of project-based learning activities addresses industry’s complaint that students lack practical experience (“how devices are made/work”).

The cardiograph project, including learning outcomes for the first semester and ABET student outcome for the entire project are discussed. We hypothesized that participating in these projects facilitates engagement in the course and Engineering Science major. Each learning outcome is assessed by the instructor using a custom rubric. In addition to student performance, we also consider how this project may support student engagement and retention via instructors’ reflections and student surveys. The findings demonstrated that the students were actively engaged in the project and appreciated the active learning approach. Students had minimal prior experience with complicated devices and had many concerns about completing the project. Based on faculty observations and students’ responses on surveys, students maintained engagement in the cardiograph project and experienced a sense of accomplishment, even when they did not successfully produce a working cardiograph.

Introduction

In 2009, the American Society of Mechanical Engineers (ASME) surveyed 80 ME department heads, 1,404 industry supervisors, and 1,198 early-career MEs for their Vision 2030 project. Survey results revealed that the skills managers believed required strengthening in new graduates did not match the skills faculty and early-career MEs chose. Practical experience (how devices are made/work) was chosen by 55.5% of managers as a weakness, in contrast to only 33% of department heads and 37.3% of early-career MEs [1-4].

In the Engineering Science department of Loyola University Chicago (LUC), we are developing a four-semester design project to build a functional cardiograph, which will give our students this practical experience. All engineering courses are taught using a minimal lecture style. For every 50 minute course period, the first ten to fifteen minutes are a mini-lecture to go over fine points of the homework. The remaining course period time is devoted to active learning.

Background

Active learning, which is generally defined as “any instructional method that engages students in the learning process” [5], has been demonstrated to significantly improve student performance on exams and concept inventories by about 0.5 standard deviations, compared to traditional lecture [6, 7]. This standard deviation improvement agrees with the results of an
earlier meta-analysis of small-group activities [8, 9]. Active learning also enhances student motivation [10].

Within active learning, the choice of pedagogy affects student self-regulated learning. As measured by Lord, et al., problem-based learning (PBL) leads to higher gains in self-regulated learning, compared to other active learning pedagogies [11]. Problem-based learning is “an instructional method where relevant problems are introduced at the beginning of the instruction cycle and used to provide the context and motivation for the learning that follows” [5]. It is problem-focused, student-centered, self-directed, self-reflective, and facilitative [12]. The PBL approach leads to improved performance and long-term knowledge retention [13-16].

Our PBL design project is built upon a cardiograph, or electrocardiograph, which is a digital instrument that inputs heart action potentials from electrocardiogram (ECG) electrodes, amplifies the input with a biopotential amplifier, and digitizes and processes the resulting signal [17]. The precursor to the cardiograph, the string galvanometer, was invented by Willem Einthoven in 1901 [18]. Some cardiographs are cardiac monitor modules that are integrated with other instrument modules, such as a pulse oximeter, within a larger patient monitor. A cardiac monitor module enables display of the ECG waveform and heart rate (HR) [19]. Other diagnostic cardiographs display and print the ECG waveform and HR, and screen for cardiac abnormalities in the general population [20].

Having each student build her own cardiograph over four semesters enables the students to experience PBL within a real-world context. Recently, the use of real-world examples in an introductory circuits course was examined by Gero, et al. The course was thirteen weeks long, with each week devoted to three lecture hours, one tutorial hour, and one workshop hour. The students in the course chose either a control section (n=72) taught with traditional lectures or an experimental section (n=51) in which real-world examples were integrated. For example, the real-world examples of capacitive and inductive coupling were a touchscreen and mobile phone wireless charger; the real world example of sinusoidal steady state analysis and frequency filters was spectral analysis of an ECG signal. Through pre- and post-test questionnaires, it was determined that intrinsic motivation differed significantly post-test between sections [21]. While other introductory circuits or analog electronics courses have not incorporated real-world examples, these courses have been administered using both a traditional lecture approach and a PBL approach. In a two-course sequence of introductory circuits, the mean exam grade for students in the two courses was 3.11 ±1.77 (from 0=fail to 5=excellent) for PBL students, which was significantly different from 1.93 ± 1.69 for traditional students [22]. In an introductory analog electronics course, the mean score was 70.2 ± 3.9% for PBL students, versus 58.4 ±10.8% for traditional students [23].

Additionally, building a cardiograph is an example of situated learning [24]. As described by Johri, et al., this “learning takes place not through transmission of abstract knowledge, but through engagement in the ‘knowledgeable skills’ that are realized in the everyday activities of a community [25].” Lave and Wenger first defined situated learning as “an extended period of legitimate peripheralitiy [that] provides learners with opportunities to make the culture of practice theirs [26].” Thus, engaging in the practices of a community causes one to identify as a member of the community. Solving a real-world engineering problem over several semesters may increase a student’s self-identification as an engineer [25].
The Project

In developing the curriculum for a new BS Engineering Science program at LUC, the first author embedded multi-semester projects called curricular contextual threads. For the patient monitoring contextual thread, each student builds a functional cardiograph over four semesters. The projects’ parts are embedded in ENGR 101 Introduction to Engineering Design (4 cr hr), ENGR 201 Experimental Engineering (3 cr hr), ENGR 324L Engineering Core Lab (1 cr hr), and ENGR 3x1L Specialty Lab (1 cr hr).

In ENGR 101, students learn SolidWorks, and conduct open-ended design projects in groups. In ENGR 201, students are exposed to all three specializations (biomedical, computer, or environmental engineering) through experiments. For computer engineering exposure, students learn microcontroller basics and then conduct Part II of the project. In ENGR 324L, students conduct experiments related to core engineering courses given during the same semester, as well as Part III of the project. Each specialization has its own lab course: ENGR 341L Biomedical Engineering Lab, ENGR 351 Computer Engineering Lab, ENGR 361 Environmental Engineering Lab. One experimental time slot has been reserved in each specialty lab to conduct Part IV of the project.

As shown in Figure 1, Part I, students create a customized cardiograph case and breadboard a biopotential amplifier during ENGR 101 (semester 1). The biopotential amplifier/myDAQ card/LabVIEW executable that enables student ECG waveforms to be displayed is then converted to a custom motherboard that interfaces a TI microcontroller and display, all of which sit in the case. In Part II in ENGR 201 (semester 3), students program the microcontroller to display ECG waveforms. In Part III in ENGR 324L (semester 5), students design and code digital filters that separate the ECG and respiratory waveforms, and count peaks to estimate HR and respiration rate (RR). They also design corresponding analog filters to directly observe how the incoming ECG waveform is affected. In Part IV in ENGR 3x1L (semester 6), students learn to incorporate wavelet transform pre-filters into their estimates of HR and RR, to minimize the effect of motion artifact.

We hypothesize that the patient monitoring curricular contextual thread increases engineering retention over the course of the project. This contextual thread, specifically Parts II and IV, will also be used to assess new ABET Engineering Accreditation Commission (EAC) Student Outcome (1): “An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.” New ABET EAC Student Outcomes (1) to (7) will first be evaluated during ABET visits in Fall 2019.
Part Ia: Circuit Breadboarding

Many incoming freshmen were aware that they would be creating a personalized cardiograph because this project was described to them during a Loyola Open House tour the previous year. During the eighth week of ENGR 101 in one 100 minute course meeting, the entire project was officially introduced by the first author through a PowerPoint mini-lecture. In preparation for this course meeting, the students were asked to review the learning activity handout they would use, which included links to a description of how current moves through the heart, instructions on how to use a breadboard, and instructions on how to use resistors:

1. https://www.nhlbi.nih.gov/health/health-topics/topics/hhw/electrical
3. https://learn.sparkfun.com/tutorials/resistors (up until the Power Rating section)

The handout described step-by-step how the students would breadboard the red sections of the circuit in Figure 2, which was used in a cardiograph lab experiment in [17].

![Cardiograph Circuit](image)

Figure 2. Cardiograph Circuit, modified from [11].

On the day of the course meeting, each group of three to four students worked to add the red sections to a preassembled circuit. Once a group believed its circuit was complete, the first author visually checked the circuit. If the circuit appeared complete, she connected the three lead inputs to an ECG simulator. Only if a simulated ECG waveform appeared in the LabVIEW executable did one student in the group then act as a “patient”. The patient self-positioned ECG electrodes across his/her chest, under clothing, and then connected these electrodes to the three ECG leads. To ensure patient safety, one lithium-ion battery powered the laptop, and two 9V alkaline batteries powered the circuit.
Part Ib: SolidWorks Case

During the tenth week, after three weeks of SolidWorks instruction, students were given their SolidWorks case assignment. They were shown the top (Figure 3) and bottom (Figure 4) of an Acrylonitrile Butadiene Styrene (ABS) plastic cardiograph case, which had been designed by the third author, a mechanical engineer in the medical device industry. Students were then asked to:

1. Create a model of the bottom case from a paper drawing.
2. Personalize the top case, given an .stl file.
3. Create an assembly model of the entire case.
4. Document the modeling approach and strategy.
5. Create an electronic drawing of the bottom case.

The students were given two weeks to complete the SolidWorks Case assignment.

Methodology

Participants

Thirty-five students, representing 83% of the class of 2021, participated in the study while taking ENGR 101. The sample included 18 females and 17 males. Students identified race/ethnicity as follows, including three students that identified with multiple ethnicities: 20 White, 10 Asian, 7 Latino/a, and 1 African American. Of these 35 students, three students (9%) decided to transfer to another major by the end of the semester. These students also withdrew and/or did not have passing grades in at least one of their required courses. Of the remaining 32 students, all passed ENGR 101, although two students either withdrew or failed another course in their first semester.

Methods

This study was part of an in-progress, longitudinal study tracking student retention, including factors that facilitated and inhibited retention. It included all data collected during the first semester of freshman year, which marked the beginning of the cardiograph project.

Tools

Students completed the Assessing Women and Men in Engineering (AWE) Annual survey [27, 28] (NSF HRD #0120642, http://aweonline.org/) at the beginning of their freshman year. Faculty outside of the Engineering Science department and administrative staff administered the survey online to ensure confidentiality. Faculty members, including the first and fourth authors, were not aware of which students agreed to participate in the study.

On the same day as the mini-lecture for Part Ia, the first author administered a pre-assessment to all students. Students answered open-ended questions about their prior experience building a complicated device, such as a cardiograph; what they were looking forward to; and what
Figure 3. Cardiograph top case, with dimensions in mm.

Figure 4. Cardiograph bottom case, with dimensions in mm.
concerns they had. Students also rated the following four items on a 7-point likert scale: I am engaged in active learning in this course; I can succeed in an engineering curriculum; I am satisfied with my decision about my engineering major; and I have a lot in common with the other students in my classes.

After the completion of Parts Ia and Ib during the fourteenth week, the first author administered a post-assessment during class. Students addressed open-ended questions about their “ah-ha” moments and what they most want to remember from the project. They also shared what they were most looking forward to, and concerns they had about the project in future semesters. The four close-ended items were also replicated. The second author then identified only the assessments for students that consented to participate the study for inclusion in the study sample, and compared survey results using two-sided t tests.

The first author observed student reactions to the circuit breadboarding; other faculty members assessed the students’ cardiograph case assignment using a rubric. The rubric had five performance indicators (individual part drawing, model assembly, modeling strategy, instructions followed, overall presentation of work) and four levels (exemplary, satisfactory, developing, emerging).

Findings

On the AWE Annual survey, students indicated no involvement in academic preparation activities, such as engineering camps, mentoring programs, or summer academic enrichment programs. On the pre-assessment, only five students indicated any experience with a complicated device or case, such as a cardiograph, prior to the project. Other devices included a robot, radio, battery management system and Arduino projects. Of these five, four were projects in a high school class or science fair, and one was with a relative.

When responding to an open-ended question on the AWE Annual Survey about what drew students to the Engineering Science program at LUC, nine students (26%) indicated that they selected the program due to its emphasis on active learning. For example, a student explained “The active learning aspect of this program drew me to it. The idea of having fifteen minute lectures, and hands-on activities for the rest of class was something that I really liked. Also the fact that the program is more project-based than lecture-based is more geared towards hands-on learning, which is something that helps me.” On the pre-assessment of the cardiograph project, 16 students (46%) were looking forward to the practical, hands-on experience of building the cardiograph, which was the most common response. Examples of student responses for what they are looking forward to included: “finally getting hands on with building a practical device and also creating a circuit for the first time,” “being able to build something this complicated in school, before even entering the workforce,” and “trying something new—I like hands on activities.” Students also indicated looking forward to knowledge or skills they would learn (13 students, 37%) and the accomplishment of completing the project (8 students, 23%).

On the pre-assessment, the majority of students indicated concerns about not understanding or executing an aspect of the project (21 students, 60%), such as circuits, breadboarding, and coding. Seven students (20%) mentioned concerns about being able to complete the project. Two students also indicated that they may not be motivated to complete the project, because they
were not interested in biomedical engineering. Only 7 students (20%) indicated no concerns.

During the breadboarding activity, faculty members observed high levels of student group excitement, in comparison to other class periods that did not include the extensiveness of hands-on activity. The high levels of excitement were based on the level of questioning, commitment to completing the activity during the course meeting time, and selfies taken by successful student groups with their ECG waveforms. Four groups, out of 11 total groups, were able to produce a functioning cardiograph. Groups that did not produce a functioning cardiograph were still able to classify resistors by reading the resistor color code, utilize breadboard power rails for grounding, and accurately position diodes in the circuit. SolidWorks case assignment scores ranged from 90 to 100 points, with a mean of 97.5 ± 3.6 points. Students personalized the top cases with embedded designs that ranged from a smiley face or lotus flower to the complicated Loyola Chicago logo. Scores were relatively similar between the 32 students who persisted to the second semester of Engineering Science, and the 3 students who transferred out of Engineering Science.

Students’ early concerns about not understanding how to complete the project on the pre-assessment were eased by the time of the post-test administration. Concerns about not understanding or being able to complete the task successfully—particularly since it was a new experience—diminished over time, but remained for some students. Table 1 highlights the type and number of memorable experiences students described for Part Ia and Part Ib of the project.

Table 1. Number of students’ most memorable experiences from the cardiograph circuit breadboard and cases based on post-assessment.

<table>
<thead>
<tr>
<th>Themes</th>
<th>Part Ia: Circuit Breadboarding</th>
<th>Part Ib: SolidWorks Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retaining knowledge and skills</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>Overcoming challenges</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Gaining a sense of accomplishment/efficacy</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Personalizing their product</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Producing a working, completed cardiograph</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

One of the main highlights from the experience was learning new knowledge and skills. “I gained a lot of knowledge while building the case for the cardiograph, and I feel I could apply solidworks in other projects if I need to.” Many students also mentioned learning how circuits work and the placement of jumper wires.

Students also described overcoming challenges and gaining a sense of accomplishment. “I most want to remember how confusing and overwhelming the project seemed in the beginning, but by the end realizing how cool the final product was and how we were to the goal.” For Part Ib, students mentioned the case assembly. “When the case snapped perfectly, so the top and the bottom were perfectly align.” Even though many groups did not produce a working cardiograph, a few students noted seeing the completed cardiograph function. Finally, some students valued the opportunity to personalize their case. “I would like to remember personalizing the top cover
of the case. Some ah-ha moments would be when I finished personalizing the top cover and when I realized what some of the measurements for the bottom were supposed to be.” The impact of this project for students both related to learning knowledge and skill, as well as to learning from the process.

Based on Table 2, students agreed that they could succeed in the engineering curriculum. Although these scores did not change between the pre- and post-assessments, the scores were significantly higher on these assessments than on the AWE survey taken at the beginning of the semester (p = 0.01). Similarly, students slightly agreed to agreed that they have a lot in common with other students in their classes. Although these scores did not change between the pre- and post-assessments, the scores were significantly higher on these assessments than on the AWE survey taken at the beginning of the semester (p = 0.00). On average, students strongly agreed that they were engaged in active learning in the course, and this remained constant on the pre- and post-assessment. Students also reported being slightly satisfied to satisfied with their choice of engineering major.

Table 2. Students’ responses on the AWE, Pre-assessment, and post-assessment.

<table>
<thead>
<tr>
<th></th>
<th>AWE</th>
<th>Pre-assessment</th>
<th>Post-assessment</th>
</tr>
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<tbody>
<tr>
<td>I can succeed in an engineering curriculum.</td>
<td>4.7 (0.7)</td>
<td>5.1 (1.0)</td>
<td>5.1 (1.0)</td>
</tr>
<tr>
<td>I am satisfied with my decision about my engineering major.</td>
<td>Don't know (n, %)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>I have a lot in common with other students in my classes.</td>
<td>3.3 (0.9)</td>
<td>4.6 (1.3)</td>
<td>4.5 (1.4)</td>
</tr>
<tr>
<td>I am engaged in active learning in this course.</td>
<td>Don't know (n)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Discussion

Students entering the undergraduate Engineering Science program had minimal, hands-on experience with complicated devices. Some students explicitly described that their rationale for joining the program was due to the hands-on, active learning approach. Students perceived the cardiograph project as an opportunity to engage in active learning. Despite the difficulty of the project and anticipated concerns, in general, students remained engaged in cardiograph project and their Engineering Science major. In addition to learning content knowledge and skills, some students also learned from the opportunity to overcome a challenge and experienced a sense of accomplishment from what they produced.

Given that active learning approaches are pervasive in the curriculum, it is difficult to
differentiate the specific impact of the cardiograph project in comparison to other curricular elements. The course in which the cardiograph project was implemented, ENGR 101, also includes an open-ended freshman design project, which has been demonstrated to significantly increase engineering retention [29].

As students became more comfortable with the Engineering Science program from weeks 3 to 8, their beliefs that they could succeed and that they had a lot in common with peers may have naturally increased. This would explain the increased scores between the AWE and pre-assessment surveys. The first two project activities, circuit breadboarding and the SolidWorks case assignment, were constructed to be inclusive, rather than demanding. Completion of these relatively simple Part I project activities might not elicit feelings of engineering identification that more complicated activities, such as programming a microcontroller to display ECG waveforms in Part II of the project, would elicit. Thus, Part I may not have facilitated situated learning, which would explain constant scores from pre- to post-assessment.

We believe the high student response scores may also reflect students’ intrinsic motivation. Part I of this project provided early opportunities for engineering students to build products. First-semester freshmen were visibly excited when their own ECGs (or that of group member) were continuously displayed on a LabVIEW graph, and took selfies with the ECG graph. Students spent much more time personalizing their cases than was necessary to obtain 10/100 points for the SolidWorks Case assignment. Both activities may have increased student interest (sense of interest), student autonomy (sense freedom, choice, and control), and student value (satisfaction of personal goals). These three factors affect intrinsic motivation, as described by the Four-Domain Development Diagram for designing effective learning experiences [30]. High intrinsic motivation, which includes high interest, may lead to increased engineering persistence [31, 32].

A limitation of this study is the lack of a control or comparison group that did not engage in the cardiograph project, or in other forms of active learning. We are unable to provide a control group at LUC, as our entire curriculum is built on active learning.

Conclusion

This study affirms the presence of students’ engagement in active learning in the face of a challenging, demanding task, such as the cardiograph project. Due to limitations of the study design, conclusions cannot be drawn about the impact of this pedagogical strategy, in comparison to other strategies, on student engagement, situated learning and student performance. With the longitudinal design, this study will continue to explore the impact of the multi-semester cardiograph project on situated learning, student engagement, student performance, and student self-efficacy, which could support student retention in engineering programs. The cardiograph project provides students with the practical experience of how devices are made/work that students and industry desire in Engineering programs.

References


