Building a Functional Cardiograph Over Four Semesters: Part 2 – Programming a Microcontroller

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Abstract

In this paper, we present the second 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”) [1].”

Introduction

The BS Engineering Science program at Loyola University Chicago (LUC) began in 2015, and is steeped in active learning. In the spirit of U.S. Air Force Academy engineering teaching [2-4], all LUC 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” activities [1], which have been demonstrated to increase student performance [5-8] and enhance student motivation [9].

Background

The curriculum includes problem-based learning (PBL), “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” [10]. Compared to other active learning pedagogies, PBL results in increased gains in self-regulated learning [11]. It also leads to improved performance and long-term knowledge retention [12-15].

In a recent American Society of Mechanical Engineering (ASME) survey, 55.5% of 1,404 industry engineering supervisors rated practical experience (how devices are made/work) as a weakness of new graduates [16-19]. To address this weakness, a PBL design project was added to the curriculum. This PBL project enables students over four semesters to build a functional cardiograph, 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 [20]. The cardiograph project is one of three multi-semester projects, called curricular contextual threads, embedded in the curriculum.

Building this cardiograph is an implementation of situated learning [21], which Lave and Wenger first defined as “an extended period of legitimate peripherality [that] provides learners with opportunities to make the culture of practice theirs [22].” 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 [23].” Here, students emulate the practices (to some extent) of electrical engineers in the medical
device industry, which could cause them to identify with engineers practicing in industry. Solving a real-world engineering problem over several semesters may increase a student’s self-identification as an engineer [23].

Project Summary and Part I Results

“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) (Figure 1).

![Figure 1. LUC Patient Monitoring Curricular Contextual Thread](image)

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 [20] 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 to 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 MATLAB digital filters that separate the ECG and respiratory waveforms, and count peaks to estimate heart rate (HR) and respiration rate (RR) [1].” In Part IV in ENGR 3x1L (semester 6), students implement these filters and calculations in the TI microcontroller.

We hypothesize that the patient monitoring curricular contextual thread increases engineering retention over the course of the project.

For Part I of this study, 35 freshmen, representing 83% of the class of 2021, participated. Students completed the Assessing Women and Men in Engineering (AWE) Annual survey study [24, 25] (NSF HRD #0120642, http://aweonline.org/) at the beginning of their freshman year, while taking ENGR 101. They also completed pre- and post-assessments bookending their breadboarding and personalized SolidWorks case activities.
“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. Students also described overcoming challenges and gaining a sense of accomplishment. Students agreed that they could succeed in the engineering curriculum. 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 [1].”

Part II: ECG Waveform and Display

In preparation for Part II of this project, the second author taught students the following topics:

1. Microcontrollers (Texas Instruments (TI) MSP430) and its integrated development environment (IDE, Code Composer Studio)
2. Microcontroller operating parameters and interfacing, including general purpose input/output and timers
3. Analog to digital conversion, reset, and interrupt functions
4. Generating graphics on LCD using image reformer software

Each sophomore received his or her personalized cardiograph top case from Part I and cardiograph hardware. As shown in Figure 2, this hardware consists of three parts: 1) a custom Loyola motherboard, with the ECG biopotential amplifier and analog filters the students breadboarded in Part I, microcontroller interface circuitry and seven light-emitting diodes (LEDs); 2) a TI MSP430FR5969 LaunchPad development kit with 12-bit differential analog-to-digital converters; and 3) a Sharp LCD BoosterPack, with a 96x96 pixel display. In groups of two, students programmed their microcontrollers in C using the TI Code Composer Studio IDE (Figure 3). A simulated ECG was generated by an arbitrary function generator (Tektronix AFG1022), and served as the cardiograph input.

Given foundational C code written by the second author and TI image reformer software, students were asked to complete four tasks:

1. LED programming – Program microcontroller registers using Boolean logic to have seven LEDs blink in a systematic pattern
2. ECG signal acquisition – Acquire an ECG signal, and generate a clear and recognizable ECG profile
3. Graphics – Generate and display meaningful animations on the LCD
4. Presentation materials – Provide an accurate and concise description of how your cardiograph operates
Student results were used as evidence for achievement of new ABET Student Outcome (1). ABET Student Outcome (1) is:

an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
Methodology

Participants
Twenty-two students, representing 63% of the starting class of 2021 and all students enrolled in ENGR 201, participated in the study while taking ENGR 201. The sample included 13 females and 9 males.

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 at the beginning of the fall semester of sophomore year and during the period when Part II of the project was administered. The annual persistence survey for this longitudinal study [24] also included a 15 instruction items on the Student Response to Instructional Practices (StRIP) Instrument [26], which uses the constructs of value, positivity, participation, and distraction to measure the extent to which students are cognitively, affectively, and behaviorally invested in a class.

Tools
The cardiograph module was one of four modules taught during ENGR 201 Experiential Engineering. This module was taught from week 9 through week 14. On the same day the
cardiograph project was announced during week 9, the first author administered a pre-assessment to all students. Students answered open-ended questions about their prior experience programming hardware, such as a chip; what they were looking forward to; and what concerns they had.

On the last day of class during week 14, students gave presentations, which included project demonstrations. Presentations were assessed using a rubric (Table 1), which had four performance indicators (the tasks) and four levels (Exemplary, Satisfactory, Developing, Emerging). All faculty members who attended the presentations graded the presentations; the average grades were recorded by the second author. The second author graded the LED programming, ECG signal acquisition, and graphics tasks.

Immediately before the presentations, the first author administered post-assessments. 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. Students also repeated the 15 items on the StRIP Instrument [26].

Findings

On the pre-assessment, only four students expressed previous experience programming hardware. For example, one had worked on programming a robot in high school, and another wrote hardware and software to test chips as part of an internship.

When asked what they were most looking forward to in this phase of the project, most students (14 students, 67%) remarked that they were eager for new learning. Nine students (43%) were excited to better understand coding/programming in particular. Another nine students (43%) expressed looking forward to completing the project. Five (24%) anticipated feeling a sense of accomplishment after the task, and four (19%) were excited to share their work with future employers.

When asked about their concerns, five students (24%) indicated they were not worried about the task ahead. More commonly, however, students (13 students, 62%) expressed concern that they either did not have the skills to complete part of the project (e.g., coding/programming) (10 students, 48%) or would make mistakes (3 students, 14%). Other students (6 students, 29%) were concerned that the project would be difficult and/or take lots of time.

Even though students expressed concerns at the outset of the project, students overall demonstrated mastery of the learning objectives for the project. Engineering Science uses a threshold of 80% students achieving exemplary and satisfactory levels for all student outcome rubrics. The levels achieved for each performance indicator are shown in Table 1. The 80% threshold was not met for presentation materials.

During the presentations, faculty members observed high levels of student excitement. Students proudly demonstrated their working code: an animation during initialization, followed by ECG acquisition; as well as separate LED blinking. Though not required to receive a grade of
exemplary, several groups created complicated animations. These animations included: a squirrel pushing an acorn, a celestial object moving across the top of the Chicago skyline, a rosebud blooming and then wilting, and a dancer executing a backflip. Four of eleven student groups mentioned that they were excited to eventually acquire ECGs from a person, rather than a simulator.

Similar to faculty observations during the presentations and the outcomes from Part I of the project from ENGR 101 [1], students also indicated high levels of engagement based on the post-assessments. First, students (22, 100%) expressed wanting to remember new knowledge and skills gained from this portion of the cardiograph project. Several students (11, 50%) were particularly enthusiastic about the coding skills they gained, mentioning functions, syntax, and different types of coding. Responses included, “I was able to understand how to call functions and the syntax of C language, and how to manipulate it to do what I want”, and “I want to remember hexadecimal and how it is used in programming.” Other students remarked about “aha moments” when lights finally lit and images became clear. Some students (5, 23%) also expressed a sense of accomplishment after persevering through difficult tasks. One said they were able to accomplish “…things I never thought I could do, let alone understand.”

After completing the hardware programming, students (19, 86%) were eager for additional practical, hands-on experience with building and using the cardiograph. Seven students (32%) mentioned their excitement about using the device with a live subject. For example, one wrote, “I am most looking forward to seeing the real life application by connecting it to a real person.” Five students (23%) were looking forward to continued coding and programming, while three (14%) were eager to refine their work (e.g., increase noise reduction). Students said they looked forward to “continuing to work on the coding side of it,” and “putting it all together and fine tuning it.” In addition to interest in particular aspects of the project, some students also mentioned looking forward to having a finished product (6 students, 27%). One wrote, “I’m looking forward to creating a stand-along project that incorporates both aspects we have worked on so far and those we will work on in the future.”

Some students expressed concerns about project understanding and execution, either in general or in relation to a specific project component, after engaging in hardware programming (11 students, 50%). Within these responses, three students (14%) expressed concern about understanding how their cardiograph works. One wrote, “I’m concerned that much of the code is given to us, so we don’t necessarily know how to explain how and why everything happens.” Other students (8 students, 36%) were worried about completing specific aspects of the project (e.g., programming). Two students were concerned about using their devices with people, with one noting they were concerned about “switching from a function generator to a person as our ‘source’.” However, 10 students (45%) expressed no concerns about continuing the cardiograph project.

Table 2 provides details about students’ responses to each item on the four subscales from the beginning of the semester and after the cardiograph project. These findings demonstrate that, in general, students are engaged in the engineering curriculum. This engagement further improves, based on experiences in the cardiograph project. In particular, students ratings on the Value subscale significantly improved between the time points, and ratings on the Distraction subscale significantly decreased.
Table 1. ENGR 201 Cardiograph Project Rubric. The total number of groups, out of 11 groups total, achieving each level is listed in red.

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Exemplary</th>
<th>Satisfactory</th>
<th>Developing</th>
<th>Emerging</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED Programming (25%)</td>
<td>The LEDs blink in a designated or systematic pattern by programming the microcontroller registers using Boolean logic. <strong>11</strong></td>
<td>The LEDs can blink but not in a designated or systematic pattern. <strong>0</strong></td>
<td><strong>N/A</strong></td>
<td>The LEDs cannot blink. <strong>0</strong></td>
</tr>
<tr>
<td>ECG Signal Acquisition (25%)</td>
<td>The executable program can be used to acquire ECG signals and to generate a clear and recognizable ECG profile. <strong>0</strong></td>
<td>The executable program can be used to acquire ECG signals and to generate an ECG profile, but the profile needs improvement. <strong>11</strong></td>
<td><strong>N/A</strong></td>
<td>The executable program cannot be used to acquire ECG signals or generate a recognizable ECG profile properly. <strong>0</strong></td>
</tr>
<tr>
<td>Graphics (25%)</td>
<td>Graphics are generated to display meaningful animations on the LCD screen. <strong>11</strong></td>
<td>Graphics are displayed on the LCD screen but are shown as individual images. <strong>0</strong></td>
<td><strong>N/A</strong></td>
<td>Graphics are not displayed properly on the LCD screen. <strong>0</strong></td>
</tr>
<tr>
<td>Cardiograph Project Presentation Materials (25%)</td>
<td>The presentation provides an accurate and concise description of the cardiograph device and how it operates. The visual presentation materials meet professional standards, and are well-integrated into the presentation. <strong>4</strong></td>
<td>The presentation provides an accurate and concise description of the cardiograph device and how it operates. The visual presentation materials meet professional standards, but are not well-integrated into the presentation. <strong>1</strong></td>
<td>The presentation provides a description of the cardiograph device and how it operates, but the description contains some errors. The visual, audio, or other presentation materials do not meet professional standards. <strong>6</strong></td>
<td>The presentation provides an incomplete description of the cardiograph device and how it operates. Student fails to include visual presentation materials, or materials chosen are inappropriate. <strong>0</strong></td>
</tr>
</tbody>
</table>
With respect to their experiences during hardware programming, students reported high levels of engagement. Students reported the highest levels of participation (average scale item $M=4.62$), saying they were often to very often participating while trying their hardest without rushing. Students also reported feeling very positive (average scale item $M=4.45$) about their project experiences. They felt the instructor had their best interest at heart, felt positive toward the instructor, and enjoyed the activity. Students also highly valued (average item $M=4.41$) the project. They reported that the effort and time required to complete the project were worthwhile. Unsurprisingly, students reported almost never being distracted (average item $M=1.35$) during the project. Students said they were authentically engaged, remaining focused at the task at hand without distracting their peers.

Discussion

Typically, engineering and computer engineering students take a microprocessor/microcontroller course during their junior year. Biomedical engineering students may take this course, if their curriculum has a medical instrumentation focus. Environmental engineering students do not take this course. Here at LUC, all engineering students are exposed to microcontrollers during their fall semester of sophomore year. They are in the only engineering major offered at LUC, Engineering Science, and begin to specialize in either biomedical, computer, or environmental engineering in the spring of junior year.

During spring of freshmen year, LUC students learned Java when they took COMP170 Introduction to object-Oriented Programming. Given primers in microcontrollers, IDE, analog-to-digital conversion, and LCD graphics, sophomores were then able to successfully program LEDs, acquire a simulated ECG signal, display animations, and present descriptions of their work. Their engagement and performance in cardiograph tasks may be tied to situative learning, as several groups stated they were looking forward to the next step of connecting their cardiograph to a person, rather than to a simulator. Working towards their goal of a functional medical device encouraged the students to reach high levels of achievement.

Reviewing Student Outcome results in Table 1, 100% of student groups were able to reach exemplary and satisfactory levels for LED programming, ECG signal acquisition, and graphics tasks. Students’ early concerns about not understanding how to complete the project on the pre-assessment were eased by the end of the project. Post-assessment results also affirmed high levels of engagement and learning for students with the project, even in comparison with students’ general experiences with the problem-based learning approach across the curriculum. However, only 45% of student groups (less than the 80% threshold) reached these levels in their presentations. The six presentations rated developing had errors in the cardiograph hardware/software description or the presentation materials did not meet professional standards. When ENGR 201 is next given in fall, 2019, instructions for presentations will include guidelines for their PowerPoints and a cardiograph hardware/software checklist. This description of performance indicator achievement and plans for increasing achievement next year will be included in the Criterion 4: Continuous Improvement section of our ABET Self-Study Report.

The findings in this study are consistent with other research on non-traditional approaches to engineering curricula. For example, in the first planning year of highly regarded Olin College
Table 2. Means (M) and standard deviations (SD) for sophomore responses to items from the Student Response to Instructional Practices (StRIP) Instrument by subscale and item pre- and post-activity.

<table>
<thead>
<tr>
<th>Subscale</th>
<th>Beginning of Semester</th>
<th>Post-activity Week 14</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td><strong>Value Subscale</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt the time used for the activity was beneficial.</td>
<td>4.00 (0.95)</td>
<td>4.36 (0.79)</td>
<td>0.36</td>
</tr>
<tr>
<td>I saw the value in the activity.</td>
<td>4.08 (0.90)</td>
<td>4.45 (0.67)</td>
<td>0.37</td>
</tr>
<tr>
<td>I felt the effort it took to do the activity was worthwhile.</td>
<td>3.75 (0.97)</td>
<td>4.41 (0.80)</td>
<td>0.66</td>
</tr>
<tr>
<td>Average item response on Value Subscale</td>
<td>3.94 (0.94)</td>
<td>4.41 (0.65)</td>
<td>0.47*</td>
</tr>
<tr>
<td><strong>Positivity Subscale</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt positively towards the instructor.</td>
<td>4.17 (0.72)</td>
<td>4.41 (0.67)</td>
<td>0.24</td>
</tr>
<tr>
<td>I felt the instructor had my best interests in mind.</td>
<td>4.67 (0.65)</td>
<td>4.59 (0.59)</td>
<td>-0.08</td>
</tr>
<tr>
<td>I enjoyed the activity.</td>
<td>3.83 (0.72)</td>
<td>4.36 (0.66)</td>
<td>0.53</td>
</tr>
<tr>
<td>Average item response on Positivity Subscale</td>
<td>4.22 (0.70)</td>
<td>4.45 (0.51)</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>Participation Subscale</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I participated actively (or attempted to).</td>
<td>4.33 (1.23)</td>
<td>4.45 (1.30)</td>
<td>0.12</td>
</tr>
<tr>
<td>I tried my hardest to do a good job.</td>
<td>4.75 (0.45)</td>
<td>4.71 (0.46)</td>
<td>-0.04</td>
</tr>
<tr>
<td>I pretended to participate in the activity. (R)</td>
<td>4.67 (0.65)</td>
<td>4.95 (0.22)</td>
<td>0.28</td>
</tr>
<tr>
<td>I did not actually participate in the activity. (R)</td>
<td>5.0 (0.00)</td>
<td>4.59 (1.18)</td>
<td>-0.41</td>
</tr>
<tr>
<td>I rushed through the activity. (R)</td>
<td>4.42 (0.67)</td>
<td>4.59 (0.67)</td>
<td>0.17</td>
</tr>
<tr>
<td>I gave the activity minimal effort. (R)</td>
<td>4.75 (0.62)</td>
<td>4.86 (0.35)</td>
<td>0.11</td>
</tr>
<tr>
<td>Average item response on Participation Subscale</td>
<td>4.65 (0.60)</td>
<td>4.62 (0.42)</td>
<td>-0.03</td>
</tr>
<tr>
<td><strong>Distraction Subscale</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I distracted my peers during the activity.</td>
<td>1.50 (0.91)</td>
<td>1.32 (0.48)</td>
<td>-0.18</td>
</tr>
<tr>
<td>I talked with classmates about other topics besides the activity.</td>
<td>2.17 (0.94)</td>
<td>2.14 (0.99)</td>
<td>-0.03</td>
</tr>
<tr>
<td>I surfed the internet, checked social media, or did something else instead of doing the activity.</td>
<td>1.08 (0.29)</td>
<td>1.05 (0.21)</td>
<td>-0.03</td>
</tr>
<tr>
<td>I pretended to participate in the activity.</td>
<td>1.33 (0.65)</td>
<td>1.05 (0.22)</td>
<td>-0.28</td>
</tr>
<tr>
<td>I rushed through the activity.</td>
<td>1.58 (0.67)</td>
<td>1.41 (0.67)</td>
<td>-0.17</td>
</tr>
<tr>
<td>Average item response on Distraction Subscale</td>
<td>1.92 (0.26)</td>
<td>1.74 (0.28)</td>
<td>-0.18*</td>
</tr>
</tbody>
</table>

Response options for each item were: 1 = almost never (<10% of the time); 2 = seldom (~30% of the time); 3 = sometimes (~50% of the time); 4 = often (~70% of the time); 5 = very often (>90% of the time).
(R) = reverse item. * = statistically significant difference p < 0.05 in paired t-tests
of Engineering, an experiment was performed in which five recent high school graduates, who had not yet taken college courses, were asked to design and build a pulse oximeter in five weeks. They did not fail as expected, but built a functional device that reportedly “performed well against a hospital version of the device brought in for calibration [27].” These results spurred Olin to consider that engineering educators may be underestimating how well students learn independently, and that student engagement can significantly impact attitudes, behaviors, and motivation [27]. The Olin curriculum contains a sequence of six design courses across four years, with a “highly experiential” learning environment [28]. It is understandable that some LUC students may not feel secure in their grasp of microcontroller programming, as they programmed without taking a traditional full course in microcontrollers. During Part IV of this project, in spring of their junior year, students will first receive more microcontroller training. They will then program their TI microcontrollers with frequency-selective filters and calculations they developed in MATLAB in Part III of this project.

“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 [1].” The class of 2021, which is the basis of the study sample in this paper, originally had only 42 freshmen. To increase the total study sample, we will continue this study with the classes of 2022, 2023, and 2024.

Conclusion

Through a four-semester cardiograph project, LUC is investigating the hypothesis that curricular contextual thread problem-based learning activities increase student engagement and student retention. The findings from this second phase of the project demonstrate that students are actively engaged in the curriculum, in general, and that the cardiograph project further facilitated this engagement. Consistent with demands from the field for students to gain practical experiences, this study demonstrates that students had minimal practical experiences prior to the project and valued the practical experience through this project. This study will continue to study additional cohorts of students and subsequent semester projects in this curricular thread.

References


