EXPERIENTIAL LEARNING IN CONTROL SYSTEMS LABORATORIES AND
ENGINEERING PROJECT MANAGEMENT

BY

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DISSERTATION
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ABSTRACT

Experiential learning is a process by which a student creates knowledge through the insights gained from an experience. Kolb’s model of experiential learning is a cycle of four modes: (1) concrete experience, (2) reflective observation, (3) abstract conceptualization, and (4) active experimentation. His model is used in each of the three studies presented in this dissertation.

Laboratories are a popular way to apply the experiential learning modes in STEM courses. Laboratory kits allow students to take home laboratory equipment to complete experiments on their own time. Although students like laboratory kits, no previous studies compared student learning outcomes on assignments using laboratory kits with existing laboratory equipment. In this study, we examined the similarities and differences between the experiences of students who used a portable laboratory kit and students who used the traditional equipment. During the 2014-2015 academic year, we conducted a quasi-experiment to compare students’ achievement of learning outcomes and their experiences in the instructional laboratory for an introductory control systems course. Half of the laboratory sections in each semester used the existing equipment, while the other sections used a new kit. We collected both quantitative data and qualitative data. We did not identify any major differences in the student experience based on the equipment they used.

Course objectives, like research objectives and product requirements, help provide clarity and direction for faculty and students. Unfortunately, course and laboratory objectives are not always clearly stated. Without a clear set of objectives, it can be hard to design a learning experience and determine whether students are achieving the intended outcomes of the course or laboratory. In this study, I identified a common set of laboratory objectives, concepts, and components of a laboratory apparatus for undergraduate control systems laboratories. During the summer of 2015, a panel of 40 control systems faculty members, from a variety of institutions, completed a multi-round Delphi survey in order to bring them toward consensus on the common aspects of their laboratories. The following winter, 45 additional faculty members and practitioners from the control systems commu-
nity completed a follow-up survey to gather feedback on the results of the Delphi survey. During the Delphi study, the panelists identified 15 laboratory objectives, 26 concepts, and 15 components that were common in their laboratories. Then in both the Delphi survey and follow-up survey each participant rated the importance of each of these items. While the average ratings differed slightly between the two groups, the order of each set of items was compared with two different tests and the order was found to be similar. Some of the common and important learning objectives include connecting theory to what is implemented and observed in the laboratory, designing controllers, and modeling and simulating systems. The most common component in both groups was MathWorks software. Some of the common concepts include block diagrams, stability, and PID control.

Defining common aspects of undergraduate control systems laboratories enables common development, detailed comparisons, and simplified adaptation of equipment and experiments between campuses and programs.

Throughout an undergraduate program in engineering, there are multiple opportunities for hands-on laboratory experiences that are related to course content. However, a similarly immersive experience for project management graduate students is harder to incorporate for all students in a course at once. This study explores an experiential learning opportunity for graduate students in engineering management or project management programs. The project management students enroll in a project management course. Undergraduate students interested in working on a project with a real customer enroll in a different projects course. Two students from the project management course function as project managers and lead a team of undergraduate students in the second course through a project. I studied how closely the project management experience in these courses aligns with engineering project management in industry. In the spring of 2015, I enrolled in the project management course at a large Midwestern university. I used analytic autoethnography to compare my experiences in the course with my experiences as a project engineer at a large aerospace company. I found that the experience in the course provided an authentic and comprehensive opportunity to practice most of the skills listed in the Project Management Book of Knowledge (an industry standard) as necessary for project managers. Some components of the course that made it successful: I was the project manager for the whole term, I worked with a real client, and the team defined and delivered the project before the end of the semester.
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CHAPTER 1
INTRODUCTION

Nearly everyone who has participated in an internship, performed a laboratory experiment, or completed on-the-job training has witnessed the impact experiential learning has had on education. Experiential learning is a process by which a student creates knowledge through the insights gained from an experience. John Dewey first proposed the revolutionary idea of blending experiences with education in 1938. Then in 1946, Kurt Lewin discovered that it was important to the learning process to have some tension or conflict between participants in a training group (T-group) during the subsequent discussion about an experience. Although his findings did not become wide-spread until the 1960s, Jean Piaget started investigating how intelligence is changed by experiences in the 1920s. Since then many other scholars have contributed to the research of experiential learning and its positive impact on students (Kolb, 2014).

Laboratory experiences are a form of experiential learning and a common component of undergraduate STEM education. They provide valuable experiences for students, who benefit by connecting the theories learned in class to practice in the laboratory (Feisel & Rosa, 2005). In the laboratory, students also have opportunities for design, problem solving, and exposure to real-world issues like friction and noise that are not usually present in traditional hand-written homework assignments (Feisel & Rosa, 2005). However, laboratories require engineering departments to address challenges such as such as budget constraints, space limitations, class size, and limited teaching resources (Borgstrom et al., 2012; Dixon et al., 2002; Ionescu et al., 2013; Khan et al., 2012).

Laboratory courses are a common implementation of experiential learning in STEM. Kolb’s (2014) model of experiential learning is a cycle of four modes. The four modes include (1) concrete experience, (2) reflective observation, (3) abstract conceptualization, and (4) active experimentation. My dissertation presents three separate studies of engineering instructional laboratories and experiential learning.

Chapter 2, “Evaluating the Effectiveness of an Affordable and Portable Laboratory Kit for an
Introductory Control Systems Course,” provides a detailed comparison of two different types of
laboratory apparatuses used in the general engineering program at the University of Illinois at
Urbana-Champaign. One of the apparatuses used in this study is a laboratory kit. A proposal of
the laboratory kit functionality was presented at the 2014 Dynamic Systems and Control Conference
(Reck & Sreenivas, 2014). A description of the experiments that can be completed using the kit
was presented at the 2015 American Society of Engineering Education Annual Conference and
Exposition (Reck, 2015a). A detailed description of the code and materials for the kit was presented
at the 2015 American Control Conference (Reck & Sreenivas, 2015). A preliminary report of the
quantitative comparison of the kit to the existing equipment was presented at the 2015 Frontiers
in Education conference (Reck et al., 2015). Chapter 2 has been submitted for journal publication.
The authors for Chapter 2 are as follows (listed in order of appearance): Rebecca M. Reck, R.
S. Sreenivas, and Michael C. Loui. I designed the quasi-experiment used in Chapter 2 under the
guidance of the remaining authors.

Chapter 3, “Common Learning Objectives for Undergraduate Control Systems Laboratories,”
provides the results of two surveys of control systems faculty and industry practitioners. The goal
of these surveys was to determine common aspects of undergraduate control systems laboratories.
A preliminary analysis of the first survey is accepted to appear in the 2016 American Control
Conference. Chapter 3 has been submitted for journal publication. I am the sole author of the
conference paper and Chapter 3.

Chapter 4, “Building Project Management Capability Through an Immersive Practical Expe-
rience,” explores the experience of a project manager in an applied project management course.
While not traditionally referred to as a laboratory, my experience as a project manager in this
course was similar to other laboratories I have completed. As a project manager in the course, I
had the opportunity to problem solve and adjust my approach to management tasks, reflect on
the experience, and connect back to what I was learning in lecture. All of these experiences were
very similar to traditional laboratory experiences in technical courses. A preliminary version of
the project management experience was presented at the 2015 International Annual Conference of
the American Society for Engineering Management (Reck, 2015b). Chapter 4 will be submitted for
journal publication. I am the sole author of the conference paper and Chapter 4.

Chapter 5, “Conclusions and Future Work,” summarizes the conclusions of each study and pro-
vides details for future work. Appendix A includes survey instruments used in the study presented
in Chapter 2. Appendix B includes the survey instruments used in the study presented in Chapter 3 and additional data and charts that support the conclusions drawn in Chapter 3. Appendix C includes the interview protocol used in the study presented in Chapter 4.
CHAPTER 2

EVALUATING THE EFFECTIVENESS OF AN AFFORDABLE AND PORTABLE LABORATORY KIT FOR AN INTRODUCTORY CONTROL SYSTEMS COURSE

2.1 Introduction

Instructional laboratories are a common experience for all undergraduate students majoring in engineering, because laboratory experiences help link theory to practice (Feisel & Rosa, 2005). Unfortunately traditional on-campus laboratories require engineering departments to address challenges such as budget constraints, space limitations, class size, and limited teaching resources (Borgstrom et al., 2012; Dixon et al., 2002; Ionescu et al., 2013; Khan et al., 2012). Additionally, laboratory experiences for off-campus students are a new consideration with the rising popularity of online courses (Aktan et al., 1996; Boubaker, 2012; Hyder et al., 2009). Laboratory kits, an alternative to traditional on-campus laboratories, can solve many of the challenges listed above. Kits cost less than traditional laboratories and allow students to take home laboratory equipment to complete experiments on their own time (Sarik & Kymissis, 2010; Stark et al., 2013). Because kits are portable, they can also be shipped to students in online courses. While a laboratory kit is a viable alternative to traditional laboratories, the students should still be able to achieve the intended learning outcomes. This study compares student achievement of learning outcomes to show that laboratory kits can be an effective alternative to traditional on-campus laboratories.

2.2 Background

Laboratory experiences in control systems are especially important because it is difficult to illustrate, with traditional lecture, the complexity and nuance of applying control system concepts to a physical system (Aktan et al., 1996; Dixon et al., 2002; Kelly & Moreno, 2001). In a control systems laboratory, students typically learn to build a system, model and analyze a system, develop a controller to meet performance requirements, simulate the controller and system, observe the physical system, collect the data, and use the data to improve the system model or control tuning.
Aktan et al., 1996; Dixon et al., 2002; Ionescu et al., 2013). Although Leva (2003) believes the controls laboratory experience should prepare students for a career in control systems, these skills can also benefit students who choose not to pursue such careers. Experiments based on DC motors can help students acquire these skills for controls laboratory experiences (Gunasekaran & Potluri, 2012; Kelly & Moreno, 2001). It is straightforward to control the position of a DC motor with a proportional-integral-derivative (PID) control (Kelly & Moreno, 2001). Small DC motors with low input power are easy to integrate into laboratory kits.

Laboratory kits have become popular, because the cost of the required hardware has decreased (Sarik & Kymissis, 2010). The contents of a kit depend on the learning objectives of the laboratory and are assembled by the instructor (Borgstrom et al., 2012; Sarik & Kymissis, 2010), adapted from an existing kit (Stark et al., 2013) or purchased as a complete kit such as Lego Mindstorms NXT (Cruz-Martin et al., 2012; Kim, 2011).

The literature includes examples of laboratory kits that are similar in cost. The Arduino prototyping kit designed by (Sarik & Kymissis, 2010) costs about $95 and was designed for a multidisciplinary course on perception, light, and semiconductors. The Mobile Studio IOBoard described by (Millard et al., 2007) has multiple versions ranging in price from $80 to $130; it is primarily used in undergraduate circuits courses.

Additionally, kits have been designed for control systems courses. Students use the Science and Engineering Active Learning (SEAL) System to develop a cart with an inverted pendulum attachment (Borgstrom et al., 2012). The SEAL System kit costs about $100 plus $179 for a myDAQ from National Instruments (Borgstrom et al., 2012; Studica, 2014). The MESAbox uses an Arduino and costs approximately $180 (Stark et al., 2013). The MESABox kit includes multiple motors and sensors and is based on an off-the-shelf kit from Sparkfun that contains more components than required for the targeted course. The laboratory experiments designed for the MESABox cover a variety of controls topics including using the Arduino programming language and wiring all of the circuits. The DC motor control equipment detailed in (Gunasekaran & Potluri, 2012) includes a motor, gearbox, encoder, and $80 of hardware components to build a traditional laboratory apparatus for approximate total of $400 (Gunasekaran & Potluri, 2012; maxon motor, 2015).

On end-of-semester satisfaction survey, students report that they like to use laboratory kits (Borgstrom et al., 2012; Ionescu et al., 2013; Sarik & Kymissis, 2010). However, these studies do not present data showing whether these kits enabled students to achieve the intended learning outcomes.
Two other studies present student ratings of their own proficiency on learning outcomes before and after completing the laboratory experiments, but there are no direct measures (Gunasekaran & Potluri, 2012; Stark et al., 2013). None of these studies directly compare learning outcomes from using a kit with outcomes from a conventional laboratory apparatus. Therefore, there is no comparison to the previous equipment. This study will compare a new kit with the existing equipment and measure student achievement of learning outcomes in a control systems course.

2.3 Purpose

In this study, we aimed to measure achievement of learning outcomes and the student experience in order to compare two types of laboratory equipment. The baseline group of students used the traditional laboratory equipment, and the treatment group of students used a new laboratory kit. We have demonstrated a method for a thorough comparison of two types of laboratory equipment that is uncommon for laboratory kits. We collected several different types of data in order to determine what effectively measures achievement of laboratory learning outcomes, since there was not an existing assessment.

We sought to answer the overarching research question: What were the similarities and differences between the experiences of students who used the portable laboratory kit and students who used the traditional equipment? We refined this question into the following questions that are more specific:

1. Can students using an affordable kit achieve the same learning outcomes as students using traditional equipment? The learning outcomes are as follows:

   (a) Understand the transfer function of a system

   (b) Draw and analyze a Bode plot

   (c) Design a PID controller

2. Do students’ perceptions of their understanding of laboratory concepts differ based on the type of equipment used?

3. Does the student experience (e.g., time spent, satisfaction, feelings towards the laboratory) differ based on the type of equipment used?
2.4 Methods

This section will describe the context of the study, the laboratory kit, and the design of the quasi-experimental study in detail.

2.4.1 Context of the study

Control Systems (GE 320) was selected for the quasi-experiment. It is the first of two required control systems courses for all general engineering majors at the University of Illinois at Urbana-Champaign. The GE 320 topics include Laplace transforms, linear mechanical and electrical system modeling, transfer functions, system stability, and feedback control design to specifications. The GE 320 prerequisites are Introductory Dynamics, Introduction to Differential Equations, and either completion or concurrent enrollment in Analog Circuits and Systems. The majority of the students registered for GE 320 are general engineering majors, however, students in other majors such as mechanical engineering and industrial engineering can also enroll in the course. Most students take GE 320 during their junior year or fall semester of their senior year. In the fall of 2014, 59 students enrolled in the lecture and one of six laboratory sections. Fifty-three of these students consented to participate in this study. In the spring of 2015, 33 students enrolled in the lecture and one of four laboratory sections. Twenty-one of these students consented to participate in this study. In each semester, half of the laboratory sections used the existing equipment (baseline group) and the other sections used the new kit (treatment group). None of the authors were involved in teaching the course during the study.

During the 16-week semester, each student attended six two-hour laboratory sessions, each with a different experiment to complete. The first two experiments introduced the equipment, the next two experiments developed models of the DC motor, and the fifth experiment implemented three different position control algorithms (Reck, 2015a). The last experiment repeated system identification and control design on a new system. The learning objectives of the laboratory experiments were the same as previous semesters, and the instructions were kept as close as possible between the two types of equipment (Reck & Sreenivas, 2015). The laboratory experiments were the same for both semesters. Students worked in groups of two (or three if necessary) to complete the experiments. However, they submitted individual answers to pre-lab and post-lab exercises and individual two-page laboratory reports. Each laboratory report was worth 100 points: 20 points for pre-lab exercises, 5 points for an introduction, 25 points for describing the results, 25 points for
discussion of the results and possible sources of error, 20 points for post-lab exercises, and 5 points for grammar and format.

2.4.2 Description of the new laboratory kit and existing equipment

We developed a laboratory kit for GE 320 that would cost less and conserve space than traditional laboratory equipment. Our kit had a target budget of $100 because this approximated the cost of other affordable kits and engineering textbooks (Millard et al., 2007; Sarik & Kymissis, 2010). To ensure portability, we designed the kit to fit in a shoebox and weigh less than a pound. Even though our kit was portable, the department purchased six kits for students to use in the laboratory under the same conditions as the existing traditional equipment used in the course. The new kit designed for an introductory control systems course consisted of a Raspberry Pi (a single board computer), DC motor, a 3D printed stand, and the associated sensors. It cost about $130. A photo of the kit appears in Figure 2.1. A demonstration video of one experiment using the kit is available https://youtu.be/wGz5nd39nY4. The existing equipment included an analog computer, DC motor, sensors, oscilloscope, function generator, and multimeter, together costing about $15,000 per station (Reck & Sreenivas, 2015). A photo of the existing equipment appears in Figure 2.2. In the experiments, students implemented the control system using the Raspberry Pi (kit) or the analog computer (existing equipment). The students in the treatment group used MATLAB and Simulink to implement the control system on the Raspberry Pi. The students in the baseline group wired circuits with operational amplifiers, resistors, potentiometers, and capacitors to implement the control system on the analog computer.

2.4.3 Procedure

In the 2014-2015 academic year with approval from the Institutional Review Board (IRB #15116), we collected quantitative and qualitative data to compare student learning outcomes between the baseline group and treatment group. The data we collected to answer each research question is summarized in Table 2.1. At the beginning of each semester, we asked each student to provide consent to participate in the study or to opt out. Students were also allowed to switch laboratory sections. Only one student switched sections in order to use the new laboratory kit.

The quantitative data included exam scores and laboratory report scores. These data were provided by teaching assistants or the faculty member teaching the lecture. In addition, student
volunteers completed a concept inventory test and survey on the last day of lecture. The concept inventory test was a multiple-choice test constructed by drawing questions from a test that was previously developed by Bristow et al. (2012) to assess students’ knowledge about control systems in mechanical and mechatronics disciplines. Consequently, the original test included questions only about mechanical systems. Since students in GE 320 study both mechanical and electrical systems during lecture, we replaced the last mechanical system question with an equivalent electrical circuit question to ensure a balance between mechanical and electrical systems. A faculty member who had taught GE 320 reviewed the test to ensure the questions were suitable. The student volunteers also rated Likert scale items on an end-of-semester satisfaction survey, which appears in the Appendix. Since few students took the concept inventory and survey in the spring semester, we combined the data for these instruments for both semesters.

All students completed the same experiment in the sixth laboratory session. In this experiment, they repeated some of the same procedures as previous labs on the existing equipment or new kit. Since the sixth experiment was the same for both semesters, these scores were combined as well.

The qualitative data included laboratory observations, reflections from students’ individual laboratory reports, open-ended questions on the satisfaction survey, and focus groups. We collected data from the entire class at the same time, so we sorted the data between the treatment and baseline groups and removed data from students who did not consent to participate in the study.
We used the observations of the fall semester laboratory sessions to supplement the data from other sources as needed. In the laboratory report template, we provided the following prompt to the students for their reflection:

Please include a reflection of at least 100 words about the experiment. This can include answers to the following questions: What aspects of this laboratory assignment met or did not meet your expectations? How did this assignment surprise, excite, or frustrate you? What lessons did you learn from this assignment? What questions do you still have?

We held two focus group sessions at the end of the spring semester. We solicited student volunteers from both semesters. As an incentive to participate, we provided pizza during the session and gave each student $10 upon completion of the session. All of the student volunteers participated in a focus group. Each session took approximately 30 minutes. Both sessions were audio recorded.
Table 2.1: Data collected and corresponding to GE 320 research questions.

<table>
<thead>
<tr>
<th>Question</th>
<th>Labs</th>
<th>FA14: Exams</th>
<th>SP15: Exams</th>
<th>Concept Inventory &amp; Survey</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Can students using an affordable kit achieve the same learning outcomes as students using traditional equipment?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Understand the transfer function of a system</td>
<td>3, 4, 5, 6</td>
<td>1, Final</td>
<td>Midterm, Final</td>
<td>Concept Inventory</td>
<td></td>
</tr>
<tr>
<td>b. Draw and analyze a Bode plot</td>
<td>4</td>
<td>2, Final</td>
<td>Final</td>
<td>Concept Inventory</td>
<td></td>
</tr>
<tr>
<td>c. Design a PID controller</td>
<td>5, 6</td>
<td>Final</td>
<td>Final</td>
<td>Concept Inventory</td>
<td></td>
</tr>
<tr>
<td>2. Do students’ perceptions of their understanding of laboratory concepts differ based on the type of equipment used?</td>
<td></td>
<td></td>
<td></td>
<td>Likert items</td>
<td>Reflections, focus groups</td>
</tr>
<tr>
<td>3. Does the student experience (e.g., time spent, satisfaction, feelings towards the laboratory)?</td>
<td></td>
<td></td>
<td></td>
<td>Likert items, open response questions</td>
<td>Reflections, focus groups</td>
</tr>
</tbody>
</table>

and then transcribed. The first session included one student from each semester of the treatment group. The second session included one student from the fall semester and two students from the spring semester of the baseline group. The questions we asked during both sessions are included in the Appendix of this paper.

2.5 Results

We analyzed the data to answer each research question based on the organization summarized in Table 2.1. We started with the quantitative analysis of the exam scores and laboratory report grades to measure the achievement of the learning outcomes for the laboratory. Next, we performed an exploratory factor analysis and comparison of the survey responses between the two groups. The quantitative survey data measured the students’ satisfaction with the laboratory experience and understanding of laboratory concepts. We did not identify any major differences between the baseline group and the treatment group based on the quantitative data. Finally, we coded the qualitative data to identify differences in the students’ perceived learning and experience in the
laboratory. We did not identify any major differences through the qualitative data either. The baseline and treatment groups had similar demographics and were representative of the overall general engineering program. Table 2.2 presents the demographic characteristics of the students in both semesters, based on the course roster each semester.

Table 2.2: GE 320 demographics.

<table>
<thead>
<tr>
<th></th>
<th>Fall 2014 Treatment</th>
<th>Fall 2014 Baseline</th>
<th>Spring 2015 Treatment</th>
<th>Spring 2015 Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>17</td>
<td>18</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Female</td>
<td>10</td>
<td>8</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Class Standing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Junior</td>
<td>14</td>
<td>12</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Senior</td>
<td>12</td>
<td>11</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Other</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

2.5.1 Exam data analysis

We started the quantitative analysis of exam data by calculating descriptive statistics and plotting the data in histograms. The exam and concept inventory scores are on a scale of 0 to 100. The exams differed between each semester, because of a change in the instructor. There were two in-class midterms exams in the fall semester and one in-class final exam. There was one in-class midterm exam and a take-home final exam in the spring semester. The descriptive statistics are presented in Table 2.3. The histograms for each exam and the Concept Inventory are shown in Figure 2.3. We checked the data for outliers using Grubb’s test (Barbato et al., 2011). Exam 1 and the final exam in the fall semester baseline group, each had one low scoring outlier of 34 and 48, respectively. Once the outliers were removed, we checked the data for normality with the Jarque-Bera test for normality (Thadewald & Büning, 2007). The p-value for each of the exams was at least 0.24; therefore the data from each group and exam were approximately normal.

We selected a t-test to compare the means of each group, because the data are approximately normal and are independent. However, since the sample variances and sample size from each group were not equal, we selected the Welch’s variation of the two-sample, t-test (Welch, 1938). The null hypothesis for each t-test was the mean exam score treatment group and mean exam score baseline group were the same. The significance level was $\alpha = 0.05$ in each t-test. Based on these t-tests we cannot reject the null hypothesis. The Cohen’s d (effect size), and power were also calculated with
each test; see Table 2.3.

The power and effect size reported in Table 2.3 were based on the actual difference in the mean. Therefore the power reported is the probability of detecting a normalized difference in the means that is the reported effect size. For educational tests, an $\alpha = 0.05$ and power of 0.8 ($\beta = 0.2$) are typical values (Creswell, 2005). With these levels and the sample size of the fall exams ($n = 25$), there would be an 80 percent chance of detecting a normalized difference (effect size) of 0.8 between the means. On the basis of the power analysis and the results presented in Table 2.3, it is unlikely that there was a medium to large normalized difference ($d \geq 0.8$) in the mean exam scores between the treatment and baseline groups.

Because we performed multiple t-tests, we considered a Bonferroni-Holm correction (Shaffer, 1995). Since most the p-values are significantly above the $\alpha = 0.05$ significance level, Type II error is more of a concern than familywise error. Therefore, we did not apply a multiple comparison correction. The lack of significant differences between the exam and concept inventory scores indicates that the students achieved the intended learning outcomes at the same level of proficiency no matter what type of equipment they used in the laboratory.

<table>
<thead>
<tr>
<th>Table 2.3: GE 320 exam statistics.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>FA14 Exam 1</td>
</tr>
<tr>
<td>FA14 Exam 2</td>
</tr>
<tr>
<td>FA14 Final Exam</td>
</tr>
<tr>
<td>SP15 Midterm</td>
</tr>
<tr>
<td>SP14 Final Exam</td>
</tr>
<tr>
<td>Concept Inventory</td>
</tr>
</tbody>
</table>

2.5.1.1 Validity of concept inventory

We investigated the validity of the concept inventory test. First, a faculty member reviewed the concept inventory test. He had taught the course in the past, but not during this study. Because of the small sample size, measures of reliability were limited. The Cronbach’s alpha for the whole test was 0.13, which is very low. The Cronbach’s alphas when excluding each test item were also very low; they are presented in Table 2.4. The concept inventory items were divided into five
Figure 2.3: Histograms of exam scores and concept inventory test.
related subsets. The second and fourth subsets were directly related to the learning outcomes of the laboratory, so we investigated each subset as a separate test. This subset analysis did not produce useful results; most of the Cronbach’s alphas were negative.

Table 2.4: Cronbach’s alpha for excluding each item of the concept inventory.

<table>
<thead>
<tr>
<th>Excluding Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.16</td>
</tr>
<tr>
<td>2</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>0.11</td>
</tr>
<tr>
<td>4</td>
<td>0.19</td>
</tr>
<tr>
<td>5</td>
<td>0.10</td>
</tr>
<tr>
<td>6</td>
<td>0.10</td>
</tr>
<tr>
<td>7</td>
<td>0.11</td>
</tr>
<tr>
<td>8</td>
<td>0.08</td>
</tr>
<tr>
<td>9</td>
<td>0.13</td>
</tr>
<tr>
<td>10</td>
<td>0.10</td>
</tr>
<tr>
<td>11</td>
<td>0.19</td>
</tr>
<tr>
<td>12</td>
<td>0.12</td>
</tr>
<tr>
<td>13</td>
<td>0.12</td>
</tr>
<tr>
<td>14</td>
<td>0.16</td>
</tr>
<tr>
<td>15</td>
<td>0.16</td>
</tr>
<tr>
<td>16</td>
<td>0.17</td>
</tr>
<tr>
<td>17</td>
<td>0.11</td>
</tr>
<tr>
<td>18</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Finally, we calculated the Pearson correlation between each pair of test items. The maximum correlation between two items was 0.46 between item 10 and item 13 and the average correlation was 0.01. Almost half, 75, of the inter-item correlations were negative, however on assessment instruments, inter-item correlations should be positive. These negative correlations could also explain the low and sometimes negative Cronbach’s alphas. In general, the concept inventory covered a variety of concepts from control systems without repeating a concept. There were also several items with choices that could be correct but not the best answer available. For example, one circuit item had choices of \( R > L \), \( R < L \), \( R > 2L \), and \( R < 2L \). The choice \( R > L \) is correct. Only seven students chose the correct answer, while 14 students chose \( R > 2L \). The variety of concepts and distracting answers could also explain the results seen in the correlations.
2.5.2 Laboratory report 6 grade analysis

Laboratory 6 was the same for both the baseline and treatment groups. The students applied skills learned earlier in the semester to identify a new system (learning outcome a) and to design a controller for it (learning outcome c). Since this laboratory experiment was a cumulative experience for the students, we compared the scores on the laboratory reports between each group. First, we spot checked and corrected any grading that was not consistent with the rubric. Then we calculated descriptive statistics and tested normality for the treatment and baseline groups; see Table 2.5. The p-values of the Jarque-Bera test were 0.12 and 0.23 for the treatment and baseline groups, respectively. The distribution of the Laboratory 6 scores appeared to have short-tails, see Figure 2.4. The Shapiro-Wilk test for normality is a more robust test for normality when the data has short-tails (Thadewald & Bünning, 2007). The p-values of the Shapiro-Wilk test were 0.0016 and 0.0025 for the treatment and baseline groups, respectively. Since the data did not appear to be normal, we used the Wilcoxon Rank Sum test to compare the distributions of the two groups. Based on the Wilcoxon test and an $\alpha = 0.05$, we could not reject the null hypothesis that the distributions are the same. The laboratory 6 report scores show that the students achieved learning outcomes a and c at the same level with both types of equipment.

Table 2.5: Laboratory 6 score statistics.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Baseline</th>
<th>Wilcoxon Rank Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Laboratory 6</td>
<td>36</td>
<td>94.2</td>
</tr>
</tbody>
</table>

2.5.3 Survey data analysis

We split the Likert-scale items from the survey into two parts: laboratory satisfaction and concepts. The laboratory satisfaction items related to the third research question, does the student experience (e.g., time spent, satisfaction, feelings towards the lab) differ based on the type of equipment used? The items about concepts related to the second research question, do students’ perception of their understanding of laboratory concepts differ based on the type of equipment used? Each of the items had four Likert-scale options: strongly disagree (1), disagree (2), agree (3), and strongly
agree (4). Some students responded to a Likert items with a five, each five was changed to a four. One student rated one item between two and three, so it was rated at a 2.5. We performed an exploratory factor analysis (EFA) on each subset of items in RStudio (R version 3.1.2 and RStudio version 0.98.1091).

2.5.3.1 Laboratory satisfaction items

First, we checked the data for invalid answers. Two students responded with a five on the one to four Likert-scale, so their responses were excluded from the data set. Then we computed the Pearson correlation matrix and checked the Kaiser-Meyer-Olkin (KMO) index to determine whether the survey was appropriate for EFA (Tabachnick & Fidell, 1989). All items had at least one correlation coefficient above 0.3, except item four, and the KMO was 0.68. Usually, a KMO > 0.7 is preferred; however, a KMO > 0.6 is acceptable (Beavers et al., 2013). Therefore, we proceeded with the EFA. Next, we estimated the number of factors using the eigenvalues on a scree plot and principal component analysis (PCA). The scree plot indicated five factors, while the PCA indicated two factors. Then we ran a factor analysis on the data with three, four, and five factors. We selected a principal factor solution and an oblique rotation, “oblimin,” which is preferred in social science research because oblique rotations can account for correlations between factors (Beavers et al., 2013).

Then, we examined the communalities extracted from the resulting fit to five factors. Communal-ity measures the amount of variance that is predictable from the factors underlying it (Tabachnick & Fidell, 1989). A communality less than 0.4 is considered low. After reviewing items with low
communality and iterating the fit, we decided to remove items four, eleven, and sixteen from the data set. The communalities of these three items were below the threshold in one of the initial fits. We checked the KMO after removing each item individually and all three items. After removing all three items, the KMO index increased to 0.79. Therefore, we continued the EFA without the following items:

4. The GE 320 laboratory assignments challenged me.

11. I learned skills in the GE 320 laboratory that I could use in industry.

16. The GE 320 laboratory equipment met my expectations.

With the new set of items, we estimated the number of factors using the same methods. The estimation was three or four factors. A factor analysis was performed with both three and four factors. The root mean square error of approximation (RMSEA) with three factors was 0.032 and 0.013 four factors. An RMSEA less than 0.06 is considered a good fit for EFA (Hu & Bentler, 1999). Since both fits were below 0.06 we analyzed which items were grouped in each factor. The groups of items in three factors seemed to make more sense based on the content of the items. We also calculated a factor analysis using a popular orthogonal rotation, “verimax.” Both outputs produced the same factors. The questions, factor loadings, and Cronbach’s alphas are presented in Table 2.6. The correlation matrix, in Table 2.7, shows that there is not a strong correlation between any of the factors.

Then we analyzed the responses for each factor in the treatment and baseline groups. We aggregated the responses from each individual item into the corresponding factor. If the item had a negative loading, we inverted the responses (i.e., four became one, three became two). None of the items had missing or omitted responses. We calculated the descriptive statistics and checked for normality. None of the factors passed the normality test. Therefore, we ran a Wilcoxon Rank Sum test, on each factor and each of the three items omitted from the factor analysis to compare the distributions of the treatment and baseline groups. The statistics and p-values are summarized in Table 2.8. The null hypothesis was not rejected for factor A1, factor A3, and the removed items, with an $\alpha = 0.05$ significance level. After applying a Bonferroni-Holm correction to the p-values, factor A2 was also above the significance level of 0.05. Based on these p-values, we concluded that the student experience probably does not differ based on the type of equipment used.
Table 2.6: Simple factor structure using principal axis EFA with oblimin rotation for satisfaction items ($\alpha = 0.86$).

<table>
<thead>
<tr>
<th>Survey Questions</th>
<th>Factor Loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
</tr>
</tbody>
</table>

**Factor A1: Laboratory objectives and connection with lecture ($\alpha = 0.84$)**

1. I am satisfied with the GE 320 laboratory. 0.87
2. The GE 320 laboratory covered enough content. 0.42
3. The GE 320 laboratory assignments reinforced topics from lecture 0.58
4. I achieved the objectives of the GE 320 Laboratory 0.56 -0.31
5. The GE 320 laboratory helped me learn concepts discussed in lecture. 0.72
6. I understood the objectives of the GE 320 laboratory 0.43 0.56
7. I did not learn anything in the GE 320 laboratory -0.54 -0.37
8. The GE 320 laboratory met my expectations. 0.53
9. The GE 320 laboratory helped me understand lecture concepts discussed in lecture. 0.43 0.56
10. I felt frustrated with the GE 320 laboratory in more than half of the laboratory sessions. -0.58
11. The GE 320 laboratory equipment was easy to use. 0.66
12. The GE 320 laboratory equipment was a distraction to learning concepts from lecture. 0.38 0.47
13. The GE 320 laboratory equipment aided my learning of course material. 0.38 0.47
14. I felt frustrated with the GE 320 laboratory equipment in more than half of the laboratory sessions. -0.58
15. I would recommend that students use the same equipment I used in future GE 320 laboratories. 0.99

Note: abs(loadings) < 0.3 are omitted.

Table 2.7: Factor correlation matrix for satisfaction items.

<table>
<thead>
<tr>
<th></th>
<th>Factor A1</th>
<th>Factor A2</th>
<th>Factor A3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor A1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor A2</td>
<td>0.50</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Factor A3</td>
<td>0.15</td>
<td>0.28</td>
<td>1</td>
</tr>
</tbody>
</table>

2.5.3.2 Concept items

We followed the same EFA procedures for the concept items in the survey. The concept items were split into two groups. Items 1-10 included the instructions “The GE 320 laboratory (this in-
Table 2.8: Descriptive statistics of laboratory satisfaction factors and items excluded from factors.

<table>
<thead>
<tr>
<th># of Items</th>
<th>Treatment (n = 24)</th>
<th>Baseline (n = 21)</th>
<th>p-value</th>
<th>p-value adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor A1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.22 0.78</td>
<td>2.17 0.85</td>
<td>0.56</td>
<td>1.00</td>
</tr>
<tr>
<td>Factor A2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.85 0.74</td>
<td>2.50 0.74</td>
<td>0.03</td>
<td>0.17</td>
</tr>
<tr>
<td>Factor A3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.33 0.75</td>
<td>2.36 0.93</td>
<td>0.92</td>
<td>1.00</td>
</tr>
<tr>
<td>Item 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.67 0.48</td>
<td>3.48 0.75</td>
<td>0.46</td>
<td>1.00</td>
</tr>
<tr>
<td>Item 11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.25 0.85</td>
<td>2.40 0.86</td>
<td>0.61</td>
<td>1.00</td>
</tr>
<tr>
<td>Item 16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.67 0.64</td>
<td>2.76 0.55</td>
<td>0.47</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Note: The students did not omit responses for any of the laboratory satisfaction items.

cludes the pre-lab questions, experiments, and post-lab questions, but does not include homework assignments or lectures) helped me learn the following topics.” Items 11-17 included the instructions: “It was easy to understand how to complete the following tasks with the GE 320 laboratory equipment.”

We started by calculating the KMO and estimating the number of factors. The KMO = 0.7 for the whole set. The scree plot of the eigenvalues indicated two, three, or four factors, and the PCA indicated three factors. The communalities from the first fit indicated that items two and seven were candidates for exclusion. We tried dividing the concept items into two, three, and four factors, none of them resulted in a fit with an acceptable RMSEA. The KMO increased to 0.71 with just item two removed and decreased to 0.69 with just item seven removed. Because the concepts tested by these items, Laplace transforms and MATLAB/Simulink, were not directly related to any other concept asked in these items, they were removed. The KMO without both questions was 0.71. The estimated number of factors also stayed the same.

The factor analysis with four factors had the lowest RMSEA = 0.11 and all communalities were greater than 0.4. While the fit is not as good a statistically, the items in the factors make logical groups. After an orthogonal rotation, the factors were the same. The summary of factors and respective Cronbach’s alphas are in Table 2.9. The correlation matrix, in Table 2.10, shows that there is not a strong correlation between any of the factors.

Then we analyzed the responses for each factor in the treatment and baseline groups. We aggregated the responses from each individual item into the corresponding factor. There were 11 total responses missing from the concept items (see column n_m of Table 2.11). We calculated
Table 2.9: Simple factor structure using principal axis EFA with oblimin rotation for concept items ($\alpha = 0.84$).

<table>
<thead>
<tr>
<th>Survey Questions</th>
<th>Factor Loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B1</td>
</tr>
<tr>
<td><strong>Factor B1: System identification ($\alpha = 0.83$)</strong></td>
<td></td>
</tr>
<tr>
<td>12. Identify the plant (system) to be controlled using first principles (measuring armature resistance, inductance, etc.)</td>
<td>0.60</td>
</tr>
<tr>
<td>13. Identify the plant (system) to be controlled using step response.</td>
<td></td>
</tr>
<tr>
<td>14. Identify the plant (system) to be controlled using frequency response.</td>
<td></td>
</tr>
<tr>
<td><strong>Factor B2: Implementing PID controllers ($\alpha = 0.86$)</strong></td>
<td></td>
</tr>
<tr>
<td>15. Design various PID controllers.</td>
<td>0.62</td>
</tr>
<tr>
<td>16. Implement PID controllers with the real motor.</td>
<td>0.90</td>
</tr>
<tr>
<td>17. Test the PID controllers with the real motor.</td>
<td>0.86</td>
</tr>
<tr>
<td><strong>Factor B3: Control systems and related components ($\alpha = 0.79$)</strong></td>
<td></td>
</tr>
<tr>
<td>1. Circuits</td>
<td>0.79</td>
</tr>
<tr>
<td>4. Types of controls</td>
<td>0.40</td>
</tr>
<tr>
<td>6. Design of control systems</td>
<td>0.50</td>
</tr>
<tr>
<td>8. Design of PID controls</td>
<td>0.44</td>
</tr>
<tr>
<td>9. Design of lead-lag controls</td>
<td>0.52</td>
</tr>
<tr>
<td>11. Tune sensors used to measure speed and position</td>
<td>0.61</td>
</tr>
<tr>
<td><strong>Factor B4: System related concepts ($\alpha = 0.76$)</strong></td>
<td></td>
</tr>
<tr>
<td>3. System identification</td>
<td>0.49</td>
</tr>
<tr>
<td>5. System stability</td>
<td>0.80</td>
</tr>
<tr>
<td>10. Frequency response</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Note: $\text{abs}(\text{loadings}) < 0.3$ are omitted.

Table 2.10: Factor correlation matrix for concept items.

<table>
<thead>
<tr>
<th></th>
<th>Factor B1</th>
<th>Factor B2</th>
<th>Factor B3</th>
<th>Factor B4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor B1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor B2</td>
<td>0.26</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor B3</td>
<td>0.36</td>
<td>0.26</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Factor B4</td>
<td>0.09</td>
<td>0.19</td>
<td>0.40</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 2.11: Descriptive statistics of concept factors and items excluded from factors.

<table>
<thead>
<tr>
<th># of items</th>
<th>Treatment (n=24)</th>
<th>Baseline (n=23)</th>
<th>p-value</th>
<th>Adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>M</td>
<td>SD</td>
<td>#</td>
</tr>
<tr>
<td>Factor B1</td>
<td>3</td>
<td>0</td>
<td>2.53</td>
<td>0.58</td>
</tr>
<tr>
<td>Factor B2</td>
<td>3</td>
<td>3</td>
<td>2.36</td>
<td>0.69</td>
</tr>
<tr>
<td>Factor B3</td>
<td>6</td>
<td>1</td>
<td>2.21</td>
<td>0.76</td>
</tr>
<tr>
<td>Factor B4</td>
<td>3</td>
<td>0</td>
<td>2.56</td>
<td>0.69</td>
</tr>
<tr>
<td>2. Laplace Transforms</td>
<td>1</td>
<td>0</td>
<td>2.33</td>
<td>0.70</td>
</tr>
<tr>
<td>7. MATLAB/Simulink</td>
<td>1</td>
<td>0</td>
<td>3.21</td>
<td>0.66</td>
</tr>
</tbody>
</table>

the descriptive statistics and checked for normality. None of the factors appeared to be normal. Therefore, a Wilcoxon Rank Sum test was run on each factor to compare the means of the two groups. The statistics and p-values for each factor and the excluded items are summarized in Table 2.11. Since most of the p-values were near the significance level, \( \alpha = 0.05 \), we applied a Bonferroni-Holm adjustment to all of the p-values (Shaffer, 1995). After the adjustment, factor three is still not above the significance level, so the null hypothesis of equal distributions is rejected. Further Wilcoxon tests indicate that the distribution of the baseline group is shifted to the right of the distribution of the treatment group.

From these results, the students’ perceptions of their understanding of system identification (factor B1), implementing PID controllers (factor B2), and system related concepts (factor B4) does not differ based on the type of equipment used. However, students in the baseline group reported that their understanding of control systems and related components (factor B3) was greater than students in the treatment group. However, this difference could arise because only the baseline group actually wired circuits to implement control systems.

2.5.4 Qualitative data analysis

We gathered qualitative data to answer the last two research questions: Do students’ perceptions of their understanding of laboratory concepts differ based on the type of equipment used? Does the student experience differ based on the type of equipment used? The qualitative data included open-ended survey questions, focus groups, student reflections, and laboratory observations. The data were divided into four cases: fall 2014 baseline, fall 2014 treatment, spring 2015 baseline, and spring 2015 treatment. We gave students in the fall 2014 treatment case pseudonyms beginning with
the letter A and students in the spring 2015 treatment case pseudonyms with B. We gave students in the fall 2014 baseline case pseudonyms beginning with C and in the spring 2015 baseline case pseudonyms beginning with D. We gave the fall TAs pseudonyms starting with F and the spring TAs pseudonyms starting with G.

We coded the data using hypothesis coding, which applies a predetermined set of codes in order to assess a hypothesis (Saldaña, 2013). We created the predetermined codes based on the research questions and laboratory observations in fall 2014. Following from the quantitative data, we hypothesized that there was not a difference in what the students perceived that they learned or in their experience. Overall, the qualitative data confirms this hypothesis.

2.5.4.1 Students’ perceptions of their understanding of laboratory concepts

In the reflections, the students mentioned several concepts that they learned including transfer functions, Bode plots, PID controllers, MATLAB, and other laboratory skills. The students were tested on only some of the reported skills. The students also described how the laboratory experiments helped them to relate the theory from lecture to a real application. However, some students indicated that they did not readily see the connections between the lecture and laboratory. Students in all four cases mentioned all of the above circumstances.

2.5.4.1.1 Laboratory concepts covered on exams. In all four cases, students reported that they learned how to derive transfer functions from experimental data (learning outcome a). For example,

The lab this week taught us how to obtain a transfer function by measuring all the physical parameters of the system. (Camden, Experiment 3 Reflection)

This experiment helped me understand transfer function [sic] a lot better. (Camden, Experiment 4 Reflection)

I think in class it is very easy to write equations but to not really understand where they are coming from, or how they apply to experimental data. I think that the lab is doing a great job of combining the two. (Diane, Experiment 3 Reflection)

The calculation of 3 transfer functions including two first order and one second order helps me to understand transfer function more [sic]. (Anne, Experiment 4 Reflection)
It is interesting that sometimes you are able to measure all of the values to find transfer functions. I do not believe that it will always work to find different characteristics of the system. Also there is a lot of error that complies with each characteristic. These can sometimes be compounded because one value must be used to find another value. Overall it was interest [sic] to see that the transfer function could be simplified to a first order system. (Blake, Experiment 3 Reflection)

Like Camden, Diane, and Anne, other students also reported a better understanding of transfer functions after completing experiments 3 and 4. Blake went further in his reflection in comparing the complexity of measurement, sources of error, and possible simplifications. Blake’s reflection illustrates the intended lessons from experiments 3 and 4.

Students in all four cases were able to create Bode plots from experimental data (learning outcome b). For example,

I found it interesting to see how a Bode plot, which had been a mystery to me, is constructed. ... Overall, this lab really helped my conceptual understanding of how a transfer function can cause both a gain in magnitude and a phase shift. (Darren, Experiment 4 Reflection)

...it does gives [sic] us a lot of insight into how we can measure certain things from just a sine graph. It is also a cool application of bode [sic] plot to real life. (Chris, Experiment 4 Reflection)

Bode plots are a graphical representation of the frequency response of a system, the students in the treatment groups referred to the frequency response in general, rather than the Bode plot itself.

Through this lab, I learned how to calculate the transfer function of an unknown system using frequency response and step response. (Ashton, Experiment 4 Reflection)

The step response method and frequency method make us [sic] able to obtain the transfer function without mathematical models. It is also more efficient. We do not need to measure to [sic] many parameters, which we did in [sic] previous lab. This advantage can help us obtain the results with less error. (Bert, Experiment 4 Reflection)

Most students generically commented on frequency response like Bert and Ashton. A smaller number mentioned the Bode plot by name like Darren and Chris. Both Darren and Chris have
demonstrated that they understand how to create Bode plots in their reflection. Both Ashton and Bert have identified advantages of step and frequency response, which is also a useful lesson from experiment 4. All four examples above, illustrate achievement of learning outcome b.

In all four cases, students learned about implementation of various PID controllers, performance differences between variations of PID controllers, and how to determine gains for PID controllers. All of these skills are aspects of designing a PID controller (learning outcome c). For example,

Results for overshoot did not meet expectations until the very end. Knowing what values to use when trying to achieve a certain % overshoot [sic] and settling time, was frustrating at times. I learned what is involved in comparing theoretical values to experimental values obtained in the lab in order to learn the benefits and drawback of each type of controller in obtaining desired results, even if it was difficult at times. (Carrie, Experiment 5 Reflection)

It was very helpful to see how changing the values in the controllers affected the settling time and percent overshoot of the three different types of controllers. The pre-lab was also very helpful in that it showed how controllers are used with transfer functions and how all that information can be used to design controllers to help a system meet design specifications. (Dale, Experiment 5 Reflection)

...I was able to see how the gains affect the performance of all 3 of these systems. I realized that there is a delicate balance between the settling time and peak overshoot when determining the proper gain to use. Picking one that is too large or too small can cause the performance of the system to suffer, as well as lead to instability of the system. (Art, Experiment 5 Reflection)

The aspect of this lab that I enjoyed the most as [sic] creating different control systems for the DC motor. It was interesting to see how the different models affected the output of the DC motor. I also enjoyed gaining a fuller understanding of how a model can be created in Simulink to create a controller. It has been interesting to see how all the labs thus far have come together to create a better understanding of how control systems work. (Bill, Experiment 5 Reflection)

Dale and Bill identified that there were differences between the three types of controllers implemented and that changing the gains changed the overall performance. However, no one commented
on the difference in the gains between the analytical, simulation, and actual solutions. Unfortunately, the latter is also an important objective of experiment 5.

2.5.4.1.2 Laboratory skills not covered on exams. In all four cases, students reported that they enjoyed learning how to use MATLAB and Simulink. They could see how this skill would be useful in the future. While the students in the treatment group used MATLAB and Simulink in all of the experiments, the students in the baseline group used them only in the last three experiments. Representative comments about MATLAB is as follows:

I do not feel that I will use circuits in my life or future jobs and that I am much more likely to use MATLAB and Simulink. (Abbot, Experiment 6 Reflection)

For example, before taking this course, I just use Matlab to do some simple coding, but in this course I learned how to use the combination of Matlab and other software to perform the whole process from simulation to analyze. (Bert, Experiment 6 Reflection)

This was also the first time we used MatLab in this lab, which was helpful to get basic knowledge about the program. (Chad, Experiment 4 Reflection)

I enjoyed using Simulink to see the expected results graphed out and verified. (Darbey, Experiment 4 Reflection)

MATLAB and Simulink are both prominent in the control systems industry and elsewhere in engineering; therefore, it is an important skill for students to learn. However, of the five exams given in GE 320 during the study, only the spring 2015 final exam included a problem that required MATLAB. Consequently, this is an example of a skill learned in the laboratory, but not necessarily reflected in an exam score.

Beyond MATLAB and Simulink, students in all four cases learned other skills in the laboratory that are not tested on an exam. For example,

The lesson I keep learning from every lab we have is to never underestimate the degree of error that may be in your results. (Cindy, Experiment 3 Reflection)

The errors in obtaining voltages has a huge impact on the transfer function values since $K_m$ is a direct result of the voltages. (David, Experiment 4 Reflection)
Both Cindy and David recognized that there were errors in their measurements, and that the error affected the overall results. Understanding that there is error between the model and the real system is an important skill for control engineers. In the treatment group, the additional lessons were related to other physical equipment like the sensors and LEDs.

I learned how to use the new raspberry [sic] Pi and LEDs helped me to understand how duty cycle made a difference on the LED displays. (Anne, Experiment 2 Reflection)

Anne recognized how the duty cycle affected the rate at which the LEDs flashed in experiment 2. Varying the duty cycle is a common control signal for motors and actuators, including the H-Bridge used on the new kit. Unfortunately, the connection between the LED blinking exercise and the control output to the motor was not made clear to the students using the kit.

I did learn more about potentiometers and tachometers which is very interesting to me.
I found it intriguing how they take measurements and can be used as sensors. (Blake, Experiment 1 Reflection)

Blake pointed out another common step, not usually covered in lecture or homework and exam problems. In order to use feedback in a physical system, a sensor must measure the feedback signal. The connection between sensors and feedback signals was not clear to all students in experiment 1.

2.5.4.1.3 Connections between the lecture and laboratory. In all four cases, students were able to see how real world practice related to theory in class. Connecting theory to practice is a general objective of all instructional laboratories. For example,

This was a more challenging lab in that we are faced with the concept that the tools we [sic] are not always going to be the ideal versions that we work with in class. This adds an element uncertainty and a level of critical thinking that requires us to analyze why the results we have aren’t [sic] what were expected and what this means for our team’s conclusions. While this is an unforeseen difficulty I expect that this much more closely resembles problem solving in the real world than it is necessary to understand the practical limitations of the environment around us and structure our solutions to take those into account. (Cody, Experiment 2 Reflection)

It’s very easy for me as someone completely new to control systems to get frustrated with the course material because I have no idea what the implications of the math are.
Understanding how controllers are designed and optimized is much easier when I can prove my theoretical, math-based controllers are actually the best choice when input into a system. (Dean, Experiment 6 Reflection)

Specifically, it was intriguing to see the similarities and differences between the theoretical models talked about in class and 'real life' systems. (Aaden, Experiment 3 Reflection)

But this lab gave me more inspirations [sic] about what we learned in class and reminded me more of the meaning of settling time and percentage overshoot. (Brett, Experiment 5 Reflection)

However, for some students, a more explicit connection between lecture and laboratory might have aided in their learning. For example,

I felt that the labs did not correspond very well to what we learned in class. The lab would have been more understandable and beneficial if I could have related it more obvious to the concepts learned in lecture. The lab concepts were much harder to understand than the lecture concepts. (Allyssa, Survey)

There were similar comments in the other three cases.

By laboratory six, the students realized what skills they learned in the laboratory throughout the semester and that they were reapplying those skills to a new system.

...[I]t was a good capstone lab for the course. It built on everything previously learned in lecture and lab and consolidated all of those ideas. (Carl, Experiment 6 Reflection)

This lab helped my understanding of control design substantially. Knowing what values of Kp [sic] and other gains that produce an unstable system shows the need for quality design for control systems. (Dean, Experiment 6 Reflection)

...Unlike other labs where the “big picture” was not clear, this lab was much more useful in tying together the material. ... (Austin, Experiment 6 Reflection)

This lab was a nice way to wrap up the lab session. It truly helped to tie many concepts together into one cohesive experiment. (Brianna, Experiment 6 Reflection)

These comments illustrate that by laboratory 6 several students did understand how to implement and test PID controllers, which was learning outcome c.
2.5.4.1.4 Misunderstanding of concepts in the laboratory. Some students left the laboratory with a misunderstanding of control systems.

I especially enjoyed using Simulink, simply because I feel like computer software is a much more accurate description rather than actual wiring. Since faulty wiring can occur at any point, a computer will truly show what a motor SHOULD do, so any giant discrepancies between the software and wiring would likely mean faulty circuitry.

(Caleb, Experiment 4 Reflection)

Caleb’s misunderstanding is that the computer simulation provided in Simulink was also created from experimental data, differences between the actual motor and the simulation may not be due to a circuitry problem.

Although I understand the concepts of a potentiometer and tachometer gain, I do not have a strong sense of what exactly goes on inside of these devices. For example, what does it mean that the potentiometer has 340 degrees of electrical travel? We were unable to see any rotation directly because the devices spin so rapidly, so I don’t feel I fully have a sense of how they actually work. (Darren, Experiment 1 Reflection)

Darren had trouble relating the physical equipment to the data that was captured on the oscilloscope. He misunderstood that students cannot see the potentiometer rotating in the laboratory, but you can see that there is a flat region in the waveform generated by the potentiometer. The flat spot represents the 20 degrees of travel that cannot be sensed by the potentiometer and therefore cannot generate a change in voltage.

Also, it was surprising to see that the speed of the motor did not appear to have an effect on the waveform outputted by the potentiometer. (Aaden, Experiment 1 Reflection)

Aaden also had trouble connecting the physical equipment to the captured data. His misunderstanding probably stemmed from reading the scope outputs in Simulink. Multiple students commented in their reflections about confusion regarding what values were on each axis of the scopes in Simulink.

I think this was an informative lab that demonstrated controllers and how they work in real world settings. I feel that it did not tie everything together though. Using the kit we did not really learn how to build or design control circuits. Nor did we actually
demonstrate control of anything to any kind of accurate degree. It would be nice to check that we can actually control things accurately. Spinning the motor at different rates [sic] it is hard to determine how accurate the controller is. I would like to see my progress and know that I can control something. (Blake, Experiment 5 Reflection)

Modern control systems in industry are typically implemented in software using a very similar process to what was used with the laboratory kit. It is unclear if Blake misunderstood this point or wanted to learn circuits in addition to software. Blake also misunderstood the accuracy with circuits was any different from the accuracy of the software controller used with the kit. It is also not clear if he understood what was being controlled in this experiment. The motion of the motor was not very clear with the kit; however, a plot of the position of the motor was on the computer screen as the motor was moving to follow the reference signal.

2.5.4.2 Students’ experience

We also used qualitative data to gain insight into the third question: Does the student experience (e.g., time spent, satisfaction, feelings towards the laboratory) differ based on the type of equipment used? In general, we hoped that the overall experience would be similar with both types of equipment. We thought that the treatment sections might complete experiments faster than the baseline sections because we thought creating models in Simulink would be faster and less confusing than wiring the analog computer. However, that did not turn out to be the case. We examined the students’ satisfaction with the laboratory, problems with the equipment, the length of time spent on each experiment, the type of instructions, and feelings expressed by the students. We also looked at the impact of the teaching assistants (TAs) on the laboratory experience. In all of these areas, there were only minor differences identified between the treatment and baseline groups.

2.5.4.2.1 Students were satisfied with the laboratory experience. Multiple students in each case stated that they were satisfied with laboratory experience and multiple students in each case stated that they were dissatisfied. In every case, there were examples of students who liked the experience and the equipment. For instance,

My lab experience overall is quite positive for this course. (Dean, Experiment 6 Reflection)
I liked how we got to do hands on work and just apply what we learned from the textbook and lecture. It was cool just to be able to see what is going on, see the spin [sic], tachometer spinning or see the output in like real time. That was pretty exciting and reinforcing what we learned in lecture. (Belle, Focus Group)

I liked this lab and it connected very well to what we are doing in class. I am liking [sic] how we are slowly building up our knowledge each lab. (Cliff, Experiment 5 Reflection)

I found this lab to be particularly useful because it helped me become familiar with the lab equipment. Being able to familiarize myself with the various computer software (such as Raspberry Pi and Matlab [sic]) will allow me to be successful in future labs and better understand the scope of each experiment and how each component is working together to create the entire system. (Austin, Experiment 2 Reflection)

Dean and Belle both had broad positive statements about the laboratory experience. Austin and Cliff both commented on how they liked that each laboratory experiment built upon skills learned in previous experiments. Throughout the reflections, surveys, and focus groups there were other similar comments, some of them as simple as “I liked this lab” or "This lab met my expectations."

There were also positive comments about both types of equipment in each semester. For example,

For me I like how there is a motor and you really can see how the developed in to motion and the flexibility of the analog computer helped you to switch around the different transfer functions to the one you like. (Dustin, Focus Group)

I liked using matlab [sic] and Agilent because it expedited the process and it was a lot less confusing. (Calvin, Survey)

I also like how the lab was interactive; we had to make changes in real time in order to receive the most accurate results we could. (Albert, Experiment 5 Reflection)

I don’t [sic] think the lab equipment should be changed. Since my group was able to pick up on [sic] concepts fairly quickly. (Barry, Survey)

Dustin, Calvin, and Albert each mentioned a specific aspect of their respective equipment. Calvin mentioned Agilent, which is the company that produced some of the existing laboratory equipment and associated interface software Agilent VEE. Agilent VEE allowed the students to control settings
of equipment via a remote interface on a PC, which in some cases is easier than the knobs on the equipment. Other students in all four cases had both specific and general positive comments about the equipment. While there were multiple positive comments about the experience and the equipment, there were also negative comments. The negative comments ranged from specific problems with part of the equipment to more general comments about the experience. For example,

The only frustrating part about this lab was making sure to get not only the wiring of the equipment correct, but to also follow the exact steps for the computer programs or else it would crash on you. (Dustin, Experiment 1 Reflection)

The prelab and postlab question [sic] did not meet my expectations. I was so confused regarding how to find the information! I ended up randomly googling [sic] nearly every question just because the lab manual did not provide the answers to the prelab questions. (Belle, Experiment 1 Reflection)

It was pretty bad. Even though I tried my best to understand what was going on & what the prelab/postlab/lab [sic] wanted, I always felt confused or dumb. I lost a ton of little points always, and feel I’m [sic] coming away from this with the same amount of knowledge I came into it. (Cindy, Survey)

I really disliked this lab. I would have much rather had a discussion class. This lab just confused me and did nothing to help me learn the material for exams. (Adrian, Survey)

Dustin mentioned a very specific problem with the equipment itself. Other students made similarly specific comments about problems that occurred during the laboratory sessions. Both Cindy and Belle commented on the difficulty of pre-lab and post-lab questions and several students in all four cases made similar comments. The pre-lab and post-lab exercises were very similar for both types of equipment. Adrian expressed a general dislike of the laboratory experience and proposed an alternative; a few other students agreed with him.

2.5.4.2.2 Problems with the equipment occurred during the laboratory. In all four cases, students ran into problems during the experiments. While some problems, like signal noise, are expected, some students became frustrated when they encountered some problems. One prob-
lem, common to both types of equipment, was obtaining data measurements from scopes. For example,

However, I did find it relatively frustrating that our equipment was naturally inaccurate as our voltage values came out askewd [sic] a lot [sic] of the times. The other part I was not thrilled about was that in the [VEE] software, it was extremely difficult to estimate a proper value for our purposes. (Dustin, Experiment 4 Reflection)

The most challenging part of this lab was actually the collect, [sic] analysis and calculation of data. To read the peak voltage and time shift from the scope, it was hard to determine which point to read and thus there were lot of uncertainties. (Brett, Experiment 4 Reflection)

Some drawbacks of this lab were the complexity of the circuit because we had to come back and look at the teaching assistant’s configuration multiple times to make sure they were a match. (Connor, Experiment 5 Reflection)

I left this lab feeling a bit frustrated. I wanted a chance to genuinely learn the material, but the amount of glitches that were seen in the experiments made it difficult to finish in the allotted time. (Anita, Experiment 4 Reflection)

Both Dustin and Brett commented on the difficulties in obtaining accurate data. Dustin was using Agilent VEE to retrieve data from the Agilent oscilloscopes, while Brett was using the Scope block in Simulink. According to the comments from Dustin, Brett, and other students, reading scopes is a common problem for students. Connor commented on the difficulty on wiring the GP-6 analog computer, which was also a common problem area with the existing equipment. Several students also mentioned that they just copied the example wired by the TA. Anita mentioned glitches that occurred in the experiment. Unfortunately, the first section of the week experienced the largest number of problems with the kit, since it was the first group of students to use the kit.

Students in the treatment cases mentioned one unique problem about only using the computer during each experiment.

Just like in the first two experiments it is somewhat difficult to split up the work and someone is always sitting and watching for large portions of the lab while the other person is working on the computer. (August, Experiment 3 Reflection)
It is unclear from the data if other students switched which partner was using the computer or if one partner was just watching (or freeloading) as suggested by August.

2.5.4.2.3 Some experiences could have hindered learning. Beyond problems with the equipment, students specifically identified two other aspects of the experience that hindered their learning. The first one was the length of the experiments, especially experiment 4 and experiment 5. For example,

Given more [sic] it would have been interesting to try to systematically vary the gains in each system and plug them in to the transfer functions obtained in the pre-lab to try to see some pattern [sic]. (David, Experiment 5, Reflection)

This experiment took an incredibly long time compared to the others. This took away from the learning experience, as we felt compelled to rush through the latter end of the experiment. (Curt, Experiment 4 Reflection)

This lab met did not meet my expectations. We had to skip one portion of the lab and quickly rush through the last section without fully understanding the concepts as we went through it. (Adelle, Experiment 4 Reflection)

I would have liked more time to work on the lab and understand the material. I think we rushed through and lost some of the learning. (Blake, Experiment 4 Reflection)

Students in all four cases experienced at least one experiment that took longer than the scheduled two hours to complete. Several students specifically stated that the length of the experiment hindered their learning.

The type of instructions provided for each laboratory experiment was the second aspect mentioned by students that could have hindered learning. The instructions were presented in a “cookbook” style: each step was specified explicitly for students to follow. Students in all four cases made comments about the instructions. For example,

I think more theory should be put into lab sessions. Instead of just having us go through the motion and finishing the lab report. (Dawson, Focus Group)

I know that maybe in college, we should study by ourselves, and I looked up on wiki and other webpages to look for the background information. However, I [sic] still confused
about many parts of the lab procedure. The lab was straight forward, and I learned how to do the lab, but I still don’t know why to [sic] go through those procedures. (Cadence, Experiment 1 Reflection)

As I was performing the lab, I did not really understand what I was doing, but was just following the instructions and gathering data. (Abby, Experiment 4 Reflection)

I personally thought this experiment was easy to follow through. The instruction were great and we could get the results we were looking for easily. My biggest concern with this experiment is that I did not understand how all these values we were getting would relate to the final transfer function. I found it hard to compute the answers for the post-lab, and there were not sufficient enough resources for me to attempt to understand what was going on. (Brooklyn, Experiment 3 Reflection)

The comments from Abby, Brooklyn, Cadence, and Dawson are all representative examples from students in each case commenting on how they just followed instructions. While some students also commented that they found the instructions were helpful, it is unclear if they achieved the learning outcomes of the laboratory experiment or just completed each step without understanding what they were doing or why each step was completed. Students described the latter experience in the comments above.

2.5.4.2.4 Students had a wide range of feelings throughout the semester. Students in all four cases experienced a wide range of feelings throughout the semester. They expressed both strong positive such as excitement and being happy as well as strong negative feelings such as confusion and frustration. The feelings seemed to vary between experiments, but not between cases. The following quotations illustrate this variation of feelings. Examples of positive feelings are as follows:

I think I particularly enjoyed this lab because I am very straightforward result-oriented thinker and learner. (Diane, Experiment 2 Reflection)

I am excited happy [sic] there was more of an emphasis on learning the concepts than mastering the wiring. (Cole, Experiment 2 Reflection)

...we again used equipment and models to prove what we already knew was true, which I find very fascinating. (Albert, Experiment 2 Reflection)
I enjoyed this experiment. I like being able to model the Simulink and investigate the different set ups. (Blake, Experiment 2 Reflection)

Other students had similar comments about feelings in experiment 2 reflections. Students may have reacted positively to experiment 2 because they completed the experiment within the allotted two hours, and they connected the experiment to the lecture material on Laplace transforms. Similarly, in all four cases, students responded positively to experiment 6. For example,

This was the most enjoyable lab to date, as it required all of our knowledge obtained throughout the semester to be successful. (Don, Experiment 6 Reflection)

I thought this lab was a very enjoyable lab and it was a good capstone lab for the course. (Carl, Experiment 6 Reflection)

I liked the machine we remote connected to in the last lab. It thought that was interesting and a cool use of technology that we could draw data from that kind of get a more real world example that we didn’t have to struggle through building. (Audra, Focus Group)

I enjoyed using the online tool to help us achieve our graphs, and especially liked being able to input our data into MATLAB and use the data tool to read the data points more accurately. (Brianna, Experiment 6 Reflection)

Again, other students had similar positive comments about experiment 6. In experiment 6, students were able to make connections between the experiments and lecture. These connections build upon the evidence of learning presented in the previous section. Most students are also able to complete this assignment within the allotted two hours. A couple of students also had the following positive comments about experiment 5:

I hope that in the next lab we can have as much fun as we did in this one. (Bill, Experiment 5 Reflection)

Every week I am finding myself becoming prouder of my efforts to understand these complex systems. (Craig, Experiment 5 Reflection)
Experiment 5 is the longest laboratory (pre-lab, experiment, and post-lab) of the semester. Comments related to this fact tend to dominate the experiment 5 reflections. However, it is helpful to note that some students had a positive experience in experiment 5.

Unfortunately, negative feelings were also common in the surveys and reflections. However, like the positive feelings, the negative feelings mostly varied in intensity and frequency based on the experiment, not the type of equipment used.

Although my group’s output data looked good, my group faced a Simulink error that made our data repetitive and useless. (Belle, Experiment 4 Reflection)

I found this lab to be the most difficult and tedious so far. We used the entire duration of the lab, and I found as time progressed it was more frustrating simply [sic]. (Diane, Experiment 4 Reflection)

Both Belle and Diane indicated to common complaints about experiment 4: equipment problems and length. Their comments help illustrate the feelings associated with the problems mentioned in the previous two subsections. These negative feelings can also impact the students’ motivation for learning in this experiment. For example,

Adjusting the Kp and Kd [sic] values is very challenging when attempting to achieve the most efficient design for a controller. It is especially hard for me to tell when one or the other needs to be altered. They both affect the system’s waveform, but in different ways. It is also difficult to know what the perfect ratio of percent overshoot to settling time is preferred. I suppose the best method to acquire a proper design is to cross reference the design with the design specifications to ensure that each criterion is satisfied individually. (Dean, Experiment 5 Reflection)

It was especially frustrating because it was hard to see patterns in change in the systems as we changed the controls. (Clare, Experiment 5 Reflection)

...I still am unclear as to what we were trying to accomplish in this lab. There’s [sic] still a significant lack of direction or useful information unless exactly the right questions are asked in class. (Angela, Experiment 5 Reflection)

We used my lab partner’s prelab [sic] answers to setup the experiment, and it looks like they’re [sic] not right which is annoying. (Blaine, Experiment 5 Reflection)
As mentioned with the positive comments on experiment 5, negative comments like these tended to dominate the topics in reflections. Both Dean and Clare mentioned confusion about how to adjust the gain values and understand the impact on the output. Dean and Clare’s confusion is unfortunate because understanding how to adjust gains to get a desired response is the main outcome of experiment 5. Angela’s comment suggests confusion about the entire laboratory, not just gains. Regrettably, the objectives of each experiment were not consistently communicated to students in any case. Blane’s confusion stemmed from a misunderstanding of the pre-lab questions and objectives of experiment 5. Everyone’s pre-lab answers, no matter what equipment they used, did not work with the real motor because the pre-lab calculations failed to take into account the effects of friction. Understanding the differences between analytical solutions, simulation, and the implementation with the real system was a key objective of this laboratory. Unfortunately, all four quotes illustrated confusion related to the objectives of experiment 5.

During this laboratory experiment I was initially very intimidated by the equipment used. I had never used such panels involving resistors and capacitors in that way before and for a first-time user the experience was slightly overwhelming. (Corey, Experiment 2 Reflection)

Corey’s expressed a feeling that was unique to the fall 2014 baseline case. However, students in both baseline cases mentioned being confused or unsure about how to approach the wiring of the GP-6 analog computer. Therefore, there might have been more students who felt the same way as Corey, but did not explicitly state the feeling in the same way as Corey. Students in the treatment cases did not mention anything similar to Corey; however, they also did not have to use the GP-6 analog computer. Many students in both baseline cases mentioned that the analog computer was new to them and hard to understand. All of the tasks completed with the analog computer in the baseline group were moved to MATLAB and Simulink for the treatment group. Because most students had used MATLAB in previous courses but not an analog computer, the tasks in MATLAB and Simulink may not have been as overwhelming for students in the treatment group. In the fall cases, students stated some negative feelings about the whole laboratory experience. For example,

I felt like this stuff was way over my head the entire time (Cliff, Survey)

The overall lab experience was frustrating and confusing. It felt like blindly following instructions a lot of the time. (August, Survey)
Both Cliff and August mentioned negative reactions toward the laboratory experience in the survey and unfortunately, these are representative comments from a few students in each of the fall cases. There were not enough survey responses from the spring cases to understand the overall feelings toward the laboratory.

2.5.4.2.5 The teaching assistants have a direct impact on the overall experience. Students in all four cases provided both positive and negative feedback about the teaching assistants (TAs) and logistics within the laboratory sessions. The TAs were responsible for running each laboratory section, grading, and office hours. At least three TAs were assigned to GE 320 in each semester. The TAs divided the required tasks as summarized in Table 2.12. The TAs teaching laboratory sections received support throughout the semester from the laboratory manager and research team. During the week before each experiment, we met as a team to complete a dry run of each experiment and discussed logistics for each laboratory. The laboratory logistics included a discussion of the objectives of each laboratory, common mistakes made by students in the past, and development of a rubric for grading the pre-labs, reports, and post-labs. Only one TA worked with the students during each laboratory section. Each TA was responsible for grading the laboratory reports of the students in their section(s). Because of this prominent role in the laboratory setting, the TAs had a direct impact on the students’ experience in the laboratory.

Table 2.12: Teaching assistant responsibilities for each semester.

<table>
<thead>
<tr>
<th></th>
<th>Fall 2014</th>
<th>Spring 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lecture Responsibilities</td>
<td>Floyd held office hours related to lecture and graded homework</td>
<td>Office hours were split between the TAs</td>
</tr>
<tr>
<td>Laboratory Responsibilities</td>
<td>Frank was responsible for all baseline sections.</td>
<td>George was responsible for one treatment section.</td>
</tr>
<tr>
<td></td>
<td>Felix was responsible for all of treatment sections.</td>
<td>Greg was responsible for the other treatment section.</td>
</tr>
<tr>
<td></td>
<td>Garrett was responsible for both baseline sections.</td>
<td>Garrett was responsible for both baseline sections.</td>
</tr>
</tbody>
</table>

In all four cases, some students expressed gratitude for their TA in reflections. For example,

...I think that our TA did an excellent job of watching time constraints and helping us with any time-demanding tasks (for example, providing us with the numbers of where to put each wires on the various system components, or setting up each experiment beforehand and letting us refer to it as needed. (Diane, Experiment 5 Reflection)
Thank you, [Frank], for being a very helpful TA for this lab course. You were patient and helpful when we asked you questions, and my lab partner and I appreciate it. (Chad, Experiment 6 Reflection)

...the TA for the lab was extremely helpful and patient with us and that allowed us to complete the lab with less frustration. (Avery, Experiment 1 Reflection)

The TA, [Greg], was also incredibly helpful and made understanding this lab a lot less complicated. (Brooklyn, Experiment 6 Reflection)

Students in all four cases found their TA to be helpful. The perception that the TAs were helpful contributed to the overall climate of the laboratory. However, these feelings of gratitude were not consistent across all students. Each TA also received criticisms from students. For example,

Very difficult [sic]. Didn’t [sic] help me learn. Condescending and unhelpful TA [sic].
Bad experience [sic]. (Curt, Survey)

Curt commented on his perception of the TA’s attitude toward students, which contradicts the helpful TA comment earlier from Chad who had the same TA as Curt. The varying opinions in the helpfulness of their TA could be explained by the fact that they were in different sections on separate days of the week.

Personally I would have appreciated if there was more than one TA available during the lab section just so when groups had questions we didn’t [sic] have sometimes up to half an hour just to ask a yes or no question to the TA so we could continue. (Belle, Focus Group)

Belle brought up an observation that the 10:1 student to TA ratio could have been high at times. There were several points in the instructions for both types of equipment that said “Show this to your TA before proceeding.” In some labs it was difficult for one TA to keep up with progress checks and assist students with problems.

TA needs to be more informed about lab objectives and equipment (Ariane, Survey)

Ariane commented on the preparedness of the TA each week. Based on observations in the fall, the TAs in both fall cases could have been more prepared to answer technical and theoretical questions about controls. Ariane’s comment could also explain multiple requests in every case for
more detailed introductory talks by the TAs at the start of each laboratory session. Students in all four cases requested more introductory talks by the TAs before they started the experiments each week. For example,

I felt that I was able to use the equipment but was not really confident that what I was doing was correct or why I was doing it. I think it would be better if in the beginning there would be a demo or at least a little blurb about the lab that we are doing for that day. This would help create a little bit more structure in the class. (Abbot, Experiment 1 Reflection)

One thing I would change about these labs is that I would have the TAs briefly explain what the students will be learning before they start doing the lab. (Charlie, Experiment 6 Reflection)

I am still wondering whether I answered my prelab questions correctly and wish we could have a lesson on the equipment in the lab prior to actually doing everything. (Belle, Experiment 1 Reflection)

So I guess the TA can be more helpful in the sense that it ties to the lecture and goes through the lecture what concepts in the past and how it ties in to the lab experiment. (Dawson, Focus Group)

Introductory talks can serve many purposes in laboratory sections. In just a few minutes at the beginning of each laboratory section, several concepts could be cleared up for students. Introductory talks can help convey the objectives for the experiment as suggested by August and Charlie. Introductory talks can help clear up confusion from pre-lab questions as suggested by Belle. Introductory talks can also help tie the laboratory experiments to lecture as mentioned by Dawson. Unfortunately, introductory talks were not consistent despite comments in reflections in all four cases.

TAs also affected students directly when they provided feedback through grading. Students reported confusion and inconsistencies in the grading in three of the cases. The spring 2015 baseline case was the only one that did not have comments about grading; however only three perspectives (one survey response and two focus group participants) were collected outside of the reflections. Not surprisingly, students did not comment on grading in the reflections. A representative comment from the focus group is as follows:
In addition nothing was fairly graded and I lost a lot of pointless points. This lab needs to be organized better with better TA’s and/or instructors. (Calvin, Survey)

A lot of these just feel like mechanics, like grading was maybe frustrating it didn’t \textit{sic} really feel uniform or you don’t \textit{sic} really know what it would take to get the grade you wanted. (Audra, Focus Group)

It would be nice if our grade didn’t \textit{sic} depend how accurate our data results were. Because I know my group had to go back and redo whole labs because there was like a MATLAB error or something and our data was faulty. (Belle, Focus Group)

An average of laboratory scores usually counted for about 20\% of the overall grade for the course so it is understandable that students would be frustrated if they did not understand the expectations to earn an A as pointed out by Audra.

Office hours were another recurring topic related to the TAs. The two laboratory TAs in the fall did not hold office hours, but the spring TAs did hold office hours. Students in all four cases commented on office hours. For example,

In addition, there was no place for reference to get help on the pre/post labs \textit{sic}, and going to lecture TA’s office hours was not always helpful because he is not really involved with the lab. (Crystal, Experiment 6 Reflection)

It would be useful if there were office hours for this class so we could at least clarify pre and post lab \textit{sic} questions along with concepts that were not very clear in the lab. (Adelle, Experiment 4 Reflection)

The prelab was very difficult for me and I need extra office hours to fully understand the questions. (Belle, Experiment 3 Reflection)

Crystal and several other students in the fall cases commented that they thought it would be helpful to have office hours. Belle’s comment from the spring treatment case illustrated how beneficial office hours can be for students. The pre-lab and post-lab exercises did not vary much between the types of equipment, based on the students’ comments it was helpful to have time outside of scheduled laboratory sessions to ask questions.

One TA related topic was unique to the baseline groups. In both cases students made comments about just copying the wiring of the GP-6 analog computer from the TA’s example.
In the beginning everything is just holes and just follow the TA and just plug whatever in there. (Dawson, Focus Group)

We didn’t [sic] really learn much because we just wired it the same way our TA did so I didn’t [sic] really get a firm understanding of what we were wiring. (Curt, Experiment 5 Reflection)

Curt, Dawson, and similar comments from other students in the baseline group raised about the GP-6 Analog Computer. The GP-6 Analog computer was a unique component of the baseline group. The baseline group was provided a manual with sample functions wired, but not the complete function expected in the laboratory experiment. The treatment groups might not have mentioned copying because the laboratory instructions said to copy a screenshot of a Simulink model. Since all of the information was in the instructions, the students in the treatment section probably did not perceive matching the Simulink model as the baseline group perceived copying the TA for wiring.

2.5.4.2.6 Suggestions for improvement. Several students also provided constructive suggestions for improvement in the laboratory. The most frequent suggestions were about improvements to the laboratory instructions.

I would have liked to see more real world applications of these systems we were using referenced throughout the lab though. (Dustin, Experiment 5 Reflection)

It was hard for me to follow what was going on in each system, and I think it would have been easier if I had more background or explanation of what exactly happened. I also was unsure how the different values related to the damping of systems, so I would have liked to have previous knowledge on that. (Clare, Experiment 5 Reflection)

The trickiest part of the labs seems to be determining what is going on with the scope outputs, because the x-axis is never labeled, so it can be difficult to tell exactly what graph we are looking at, especially if there are multiple inputs or outputs. (Alvin, Experiment 2 Reflection)

During the lab, I realized that other students were also confused. I wonder if we can have more clear instruction to complete the lab with because I have been confused with the prelab and postlab for every lab now. (Belle, Experiment 3 Reflection)
Dustin made a good suggestion about connecting the experiments to real world applications, which is only currently provided in laboratory 6. Clare and others requested more background or context for each experiment. Alvin’s request was more specific to the confusion created while attempting to gather data from Simulink scopes and asked for more detailed instructions to be included. Belle and others also commented on the clarity of the instructions. However, many students also commented that the instructions were helpful and straightforward. There was a varying perspective on the instructions.

Some students offered some other specific suggestions that will also be taken into consideration in the future. Below are some representative suggestions.

Connection is key. As long as there is [sic] tie between lesson and lab it should be alright. (Dawson, Focus Group)

It would have been really cool to choose what kind of controller to use and try to fit within some design specifications. I know the web app would limit us in terms of what controllers were used and how they were configured, but it would have been even more fun to choose our controller type as well. (David, Experiment 6 Reflection)

I would suggest that the basic circuitry be set-up ahead of time so we’re not wasting time connecting wires and instead we can jump straight to learning about how the system actually works. (Cassidy, Focus Group)

A suggestion for this lab will be to make it more interactive, giving us more opportunities in terms of setting up the lab equipment. Feels like everything has been set up already and all we are doing is plugging in numbers and getting data. (Anton, Experiment 3 Reflection)

I am grateful for the experience, but if I were to design this lab, I would recommend a more direct approach so that the learning was done during the switch from section 1 to 2 to three [sic] as opposed to trying to understand the objective of the pre-lab. (Brad, Experiment 5 Reflection)

2.5.5 Limitations

There are several limitations in this study. It covered only one academic year, one program, and one school. The limited exposure led to a small sample size. The concept inventory test and survey
had an even smaller sample size because students volunteered to take both the concept inventory and survey during the last lecture of the semester. Only four students took the survey and concept inventory in the spring. The sample size of completed surveys was also small, just over the typical minimum 10:1 ratio of samples to factors for exploratory factor analysis (Costello & Osborne, 2005). The number of consenting participants in the spring was also close to the minimum number of samples for a student t-test (de Winter, 2013).

The TAs changed between the semesters. The spring treatment case had two TAs and the other three cases each had one TA. The TAs brought different experiences into the laboratory. For example, Greg took GE 320 as an undergraduate student and his research is related to controls, whereas Felix had never taken a controls class and fall 2014 was the first semester he was a TA.

In addition, the TAs did not consistently follow the grading rubrics. One of the TAs did not follow the grading rubric for laboratory 6, so we regraded reports from his section prior to analysis to ensure consistency between sections.

Unfortunately not all of the data we planned to collect were gathered. We were not able to observe the laboratory sections in the spring, so there is not data to explain the technical errors and excessive time spent using the laboratory kit in the spring semester. Not all of the graded laboratory reports were legibly scanned and some reports were not scanned at all, so some data were lost.

Even though the students were told their laboratory reflections would not be graded, the reflections were still turned into the TAs who were responsible for grading. Therefore, some reflections might not have been the complete picture of the experience. The students were told that only the research team would see the data from the focus groups and surveys. The audience might have influenced the responses provided.

We did not use a specific theory to inform the design of the survey or other data collected in this study. Therefore, the breadth or depth of the data in some areas may not be sufficient for a valid interpretation. For example, we focused on the equipment and assignments in the development of the instruments for this study. As a result, the survey and focus groups did not include any specific questions about the teaching staff. During the analysis, we drew conclusions about the TAs, which made sense from the data we collected. However, since we did not ask all students for feedback about the TAs, our data might not have been complete.
2.6 Discussion

In this study, we sought to answer three questions. (1) Can students using an affordable kit achieve the same learning outcomes as students using traditional equipment? (2) Do students’ perceptions of their understanding of laboratory concepts differ based on the type of equipment used? (3) Does the student experience differ based on the type of equipment used? Based on the data collected we saw little to no difference in student learning or the student experience based on the type of equipment they used. Based on the exam and concept inventory scores students using both types of equipment achieved the learning outcomes at the same level. Students’ responses in the surveys and laboratory reflections indicated that the laboratory experiences are about the same for both types of equipment, except factor B3. Factor B3 included an item about circuits, the students in the baseline group wired circuits to implement the control system during the laboratory; while the treatment group used MATLAB and Simulink to implement the control system. The difference in control system implementation could explain the difference in survey responses as well. In this section, we will explore additional factors that could influence student learning and the overall student experience in the laboratory.

2.6.1 Student learning

In this study, we explored two aspects of student learning. First, we looked at how students learn or develop mastery of a subject. Then we examined at how to assess what students have learned in the laboratory.

2.6.1.1 How students learn

Many studies have demonstrated the effectiveness of the experiential learning cycle. Experiential learning can be applied in many learning contexts, including instructional laboratories. The key to successfully implementing experiential learning cycle in a course is for students to experience all four modes of the experiential learning cycle multiple times. The four modes of the experiential learning cycle are: (1) concrete experience, (2) reflective observation, (3) abstract conceptualization, and (4) active experimentation (Kolb, 2014). The GE 320 laboratory was designed to include all four modes of Kolb’s experiential learning cycle.
2.6.1.1 **Concrete experience.** Each GE 320 experiment provided multiple iterations of a concrete experience. At least one laboratory experiment covered each of the learning outcomes. Three experiments covered transfer functions (learning outcome a), one experiment created Bode plots (learning outcome b) and two experiments implemented PID controllers (learning outcome c).

2.6.1.1.2 **Reflective observation.** The GE 320 laboratory instructions prompted students with reflective questions during the experiments. Post-lab questions also provided an opportunity for reflection and answers are turned in with the laboratory reports each week. Finally, students also completed ungraded reflections with each laboratory report. All three of these provided opportunities for reflective observation, if taken seriously.

2.6.1.1.3 **Abstract conceptualization.** In the abstract conceptualization, students should have connected their observations to theories learned in lecture or generate new theories that are specific to the laboratory experience. Based on the qualitative data, connections between laboratory and lecture were not clear to some students in each case. In addition, the objectives of each laboratory experiment were not clear to every student. Because of the unclear connections and objectives, not every student completed the abstract conceptualization mode.

There are several ways to improve connections and clarity of objectives. As Dawson stated in the focus group “connection is key.” When students make inaccurate or random connections of what is learned, they can fail to retrieve or apply it correctly (Ambrose et al., 2010). Connecting topics in lecture with laboratory experiments help students organize their knowledge. The organization of knowledge affected how students learn and use what they know (Ambrose et al., 2010). Connections help students use their laboratory experience to build upon and practice what is taught in lecture. Connections help students relate theory to practice, the objective of every STEM instructional laboratory. The connections between laboratory and lecture might be more obvious to the instructional staff because they are more experienced in control systems than the students taking their first class in control systems. Instructors should make connections to lecture and clearly state objectives for each laboratory experiment. Objectives help focus students on the important aspects of the experiment.
2.6.1.1.4 Active experimentation. Students need to test these new theories learned during other modes of the experiential learning cycle through active experimentation. Some students may not have fully experienced this mode because of the cookbook style instructions provided. In cookbook style laboratory experiments, students simply follow explicitly stated step-by-step procedures. More than one student commented that there were times when they were blindly following instructions and did not know why they were doing it. Some students also indicated that time pressure caused them to focus on completing the experiment rather than learning. Both of these reactions are confirmed in the literature. Cookbook style instructions promote mimicry over a deep understanding of the material (Truax, 2007). Additionally, demands on a student’s time can shift their focus from learning to submitting a correct report on time (Bella, 2003).

In order to gain the full benefits of this mode, the students need to actively participate in the experimentation. The student should generate procedures to test their knowledge as they understand it with TAs as more of a guide or mentor in the process. The students also need to be provided a sufficient amount of time to complete each experiment.

2.6.1.2 How to assess student learning

Student learning can be assessed and measured in a variety of ways. The most popular graded assessments are exams and quizzes; however, projects and presentations are growing in popularity in STEM classes. Graded assessments in STEM laboratories are usually reports or laboratory notebooks. Some laboratories conduct laboratory practical exams, where each individual student demonstrates skills they learned in the laboratory to an instructor. The instructional staff of GE 320 used a variety of assessments to determine the grade earned by each student. Homework, exams, and laboratory reports (including pre-lab and post-lab exercises) are components of the final GE 320 course grade.

Upon further consideration, exams and concept inventories may not accurately assess what students learned in the laboratory, whereas concepts covered by laboratory experiments were also on the exams and concept inventory, there is a significant difference in how the concepts are presented. For example, each item on the exams and the concept inventory have one answer. Each item on the exams and concept inventory test used round numbers and simplified systems to make the mathematic equations solvable by hand without a calculator or computer. The systems in the laboratory are neither simple and nor contain round numbers. Moreover, the noise, friction, and
tolerances within the real motor cause an inaccurate representation of reality in the mathematical models generated during the laboratory experiments. Therefore, there is not one correct answer. The methods used to find gains in the laboratory do not directly translate back to finding gains on an exam. Some of the skills required to design a control system in a laboratory experiment are different from the skills to create an analytical design of a control system on an exam. Therefore an in class exam may not accurately assess what skills were learned during a laboratory experiment. A recent study by (Wieman & Holmes, 2015) also concluded that exams may not be an accurate measure of what students’ achieve in an instructional laboratory.

We suggest that a more accurate assessment of learning outcomes be developed for instructional laboratories. Laboratory practical exams might be an alternative to in-class exams because they specifically cover skills that can only be demonstrated in a laboratory setting. However, practical exams are not common across all STEM laboratories. Laboratory reports and post-lab questions are another form of assessment provided they are individual work.

2.6.2 Student experience

A student’s motivation shapes their experience in a course. Ambrose et al. (2010) synthesize key concepts of student motivation from several theories developed by Atkinson (1957, 1964), Wigfield & Eccles (1992, 2000), and Ford (1992). According to Ambrose et al. (2010), motivation is comprised of value, expectancy, environment. Value and expectancy drive learning goals each student has for the course and laboratory. The value defines what a student will gain from achieving their learning goal. The expectancy drives the student’s belief that they can achieve their learning goal. Environment refers to the overall classroom climate that can range from supportive to unsupportive. Based on the qualitative data, value, expectancy, and environment contributed to the student experience in the GE 320 laboratory.

2.6.2.1 Value

Students place their own value for a course and laboratory experience. Value is comprised of three components: attainment value, intrinsic value, and instrumental value (Ambrose et al., 2010). The variation of value between students is evident throughout the qualitative data.

Students derive attainment value from the satisfaction of completing a task or goal (Ambrose et al., 2010). Attainment value was evident in the reflections when students had positive feelings
about successfully completing an experiment. Students indicated a possible decrease in value with negative comments about the amount of time spent in order to complete an experiment or pre-lab. In order to increase attainment value in the laboratory, students should be able to meet the goals of each experiment within the allotted time.

Students gain intrinsic value from the satisfaction of simply working on a task, but not the outcome of the task (Ambrose et al., 2010). Students indicated intrinsic value with positive comments about learning. Students mentioned sticking through the course and laboratory because their major concentration was control systems, which is another example of intrinsic value. Not all students derive intrinsic value from a laboratory on their own. However, a TA can encourage intrinsic value by showing their own excitement and enthusiasm for the concepts and experiments.

Instrumental value extends from the extrinsic rewards of completing a task or goal (Ambrose et al., 2010). Students derive instrumental value from good grades and other external rewards. In contrast, students loose instrumental value when they receive an unexpected low grade. Students also demonstrated instrumental value when they found connections between the laboratory and the course or their future careers. One way to increase instrumental value is for the TA to provide a real world example that relates to the experiment for the day or an example of how a skill learned in the laboratory could be useful in a future career. Additionally, the TA and professor should emphasize the connections between the laboratory and lecture components of a course.

2.6.2.2 Expectancy

Both value and positive expectancy drive motivation. Positive expectancy builds from the belief that a desired outcome is possible. In addition to having value in a goal, each student also needs to believe he can achieve the goal (Ambrose et al., 2010). Comments from students about “losing pointless points” or not knowing what it takes to get an A on the laboratory reports are clear indications that they did not believe they could succeed. While not all students expressed frustration with unclear expectations, there is still room for improvement. One way to improve expectancy would be to make sure each TA states the expectations for all laboratory assignments during the first day and provides detailed feedback and timely feedback on all assignments. Perhaps allowing students to peer review each other’s work and/or submit a revised report would also help reduce confusion about expectations.
2.6.2.3 Environment

A supportive environment also contributes to motivation. Students perceive the environment of a course in a range from supportive to unsupportive (Ambrose et al., 2010). This range was evident in the qualitative data for GE 320. One student commented that one TA was condescending and unhelpful. Several students mentioned that the fall TAs were not available enough to answer questions. Both of these situations contributed to an unsupportive environment. However, not all students agreed on the level of support provided by each TA. One way to improve the environment is to make sure the laboratory TAs hold office hours each week that there is a pre-lab or laboratory report due. Another improvement would be to make sure TAs give short introductory talks at the beginning of each laboratory session and are prepared to answer questions that arise during the experiments.

2.7 Conclusions and future work

We have shown that a laboratory kit is an acceptable alternative to traditional laboratory equipment for an introductory control systems course. Unlike previous studies that just evaluated students who used an affordable kit, we used a quasi-experiment to compare a group of students using an affordable kit to another group of students that used traditional laboratory equipment. We collected both qualitative and quantitative data to evaluate the achievement of learning outcomes and the student experience in the laboratory for both groups of students. The students’ achievement of learning outcomes, experience, and perceptions of learning do not appear to depend on the type of equipment they use in the laboratory.

Instructional objectives provide the foundation of the laboratory experience. The objectives should closely align with the rest of the course. The objectives should be clearly communicated to the students. Students should demonstrate achievement of both course and laboratory learning outcomes through assessments. Students can demonstrate achievement of course learning outcomes on exams and quizzes, but it is not clear that exams and quizzes are an accurate assessment of the achievement of laboratory learning outcomes. Students can demonstrate achievement of the laboratory learning outcomes as well; however, the assessment should cover outcomes that are not directly covered on an in-class exam, such as using MATLAB or adjusting a gain to meet performance criteria in a real system.
The specific laboratory equipment does not seem to affect the overall experience and learning outcomes, provided the equipment is functional, properly introduced, and supports the objectives of each experiment. In this study, most of the frustrations with both types of equipment arose when something did not work or the student did not feel comfortable using the equipment.

If the laboratory equipment supports the objectives of the laboratory, then the laboratory experiment design and instructional staff have more of an impact on the overall student experience and achievement of learning outcomes. Experiment design should be based on an evidence-based theory, such as experiential learning. Following from experiential learning, all students should engage actively in an experiment, rather than passively following instructions. Students can become passive participants with cookbook style laboratories. Students should also have an opportunity for guided and open reflection about what was learned in a laboratory experiment. Finally, students should be able to connect what is learned in the laboratory back to theories and topics learned during lecture. Instructional staff contributes to a supportive environment in the laboratory. A supportive environment includes setting clear expectations, providing timely feedback, being available to answer questions, and offering the assistance needed to succeed in the laboratory.

Future research includes the investigation of the use of the laboratory kit in other contexts such as allowing the students to take the kit home or in an online course. Because the control systems concept inventory did not appear to be very reliable, we will consider improvements to the test. In addition, since the current assessments do not seem to accurately measure laboratory learning outcomes, we will explore other measures of achievement of learning outcomes in laboratories.
CHAPTER 3

COMMON LEARNING OBJECTIVES FOR
UNDERGRADUATE CONTROL SYSTEMS LABORATORIES

3.1 Introduction

Laboratory experiments and projects are common components of higher education in STEM. Like other aspects of a course such as tests and homework, these experiments and projects are generally developed by the instructional staff at each university. To help instructors develop laboratories, some general guidance and evidence based practices have been published on engineering laboratories Feisel & Rosa (2005) and some disciplines like physics have very detailed research and recommendations for laboratory experiences (Wieman & Holmes, 2015). However, detailed frameworks or guidance is not available across all STEM disciplines.

Course objectives and learning outcomes form the foundation for course development. Similarly, clear laboratory objectives form the basis for laboratory design (Feisel & Rosa, 2005). Laboratory objectives define the types of experiments that should be included and inform decisions about what equipment is needed to support the experiments. Laboratory objectives are also useful in communicating what students can likely achieve in a laboratory to other instructors developing laboratory experiments. Unfortunately, objectives are often not included in the literature on engineering laboratories. This study seeks to determine a framework of accepted laboratory objectives for undergraduate control systems laboratories, a discipline with limited resources about laboratory experiences.

In addition to objectives and outcomes, this study also examines concepts and components of the laboratory apparatus for undergraduate control systems courses. Concepts are theories, topics, controller types, and techniques used to design control systems. A laboratory apparatus contains everything needed to complete a suite of experiments. In general, for a control systems laboratory, the apparatus includes the physical plant, sensors, data acquisition, controller hardware, software, and wires.
3.1.1 Previous surveys about control systems courses

In 1988, Dorato (1990) conducted a survey of control systems curricula. From this survey, he listed seven popular experiments and determined that only 38% of B.S.E.E. programs required students to take a control systems laboratory. Then in 1999, participants at a joint NSF/IEEE Control Systems Society workshop on control education discussed undergraduate curriculum issues, graduate curriculum issues, computing technologies, continuing education, and laboratory issues (Antsaklis et al., 1999). The workshop participants stressed the importance of including laboratories in control systems courses and identified seven objectives of control systems laboratories: demonstrate analytical concepts; introduce real-world issues like noise, saturation, and uncertainty; provide instrumentation and measurement; introduce broader design constraints; maintain engineering notebooks and write reports; solve problems in teams; and provide teaching experience for graduate assistants. Additionally Boubaker (2012) described laboratory experiments that could be completed with an inverted pendulum, a popular physical plant in control systems courses.

3.1.2 Review of six current control systems laboratories

To understand how control systems laboratories are described in the literature, six papers about hands-on control systems laboratories were reviewed. In these six papers, there was also confusion in terminology about objectives and learning outcomes. In two of the papers, the authors defined high-level objectives or outcomes rather than specific learning objectives: Peerless et al. (2014) listed four points of ABET Criterion 3: Student Learning Outcomes, and Stark et al. (2013) listed the same general objectives as Feisel & Rosa (2005). In the next two papers, the authors listed design requirements or detailed specifications of the laboratory apparatus instead of objectives for students: Durfee et al. (2005) listed six design requirements, and Gunasekaran & Potluri (2012) listed four design requirements. The only common design requirements in both papers were in-house support and low-cost. In the last two papers (Watkins & O’Brien Jr., 2003; Borgstrom et al., 2012), the authors listed concepts (e.g., theories, topics, or techniques) that are covered in the course and demonstrated in the laboratory. None of the concepts listed in these two papers were the same.

Of the six papers reviewed, three of them used portable kits and the other three used traditional laboratory apparatuses in a dedicated space on campus. The three kits each had different hardware platforms: Arduino (Stark et al., 2013), myDAQ (Borgstrom et al., 2012), and a custom printed
These six papers about laboratories lacked consistency in how they described control systems laboratories. Because of this inconsistency, the similarities and differences between the laboratories were unclear. If there were more clarity and consistency it would be easier adapt and apply the existing laboratories at another institution.

The difference between objectives and learning outcomes also contributes confusion among some faculty members because they do not have consistent definitions in all sources (Feisel & Rosa, 2005; Harden, 2002; Felder & Brent, 2003). In ABET’s accreditation guidelines, however, objectives and learning outcomes have specific definitions (Felder & Brent, 2003). Following (Felder & Brent, 2003), this study defines a learning objective as an observable student activity that shows what knowledge or skill has been acquired in the laboratory. A learning outcome is defined as the knowledge or a skill that a student was expected to acquire upon completion of the laboratory.

Previous literature has provided some general laboratory objectives. Feisel & Rosa (2005) list general objectives of engineering laboratories and Antsaklis et al. (1999) list seven high-level objectives of control systems laboratories, such as demonstrating analytical concepts. This study seeks to provide more detail and consistency than previous studies by defining detailed sets of objectives, concepts, and laboratory components that are important for a laboratory in an undergraduate control systems course.

3.2 Purpose

The purpose of this study is to bring faculty who teach control systems to a consensus on the most important learning objectives, concepts, and components of a laboratory apparatus for an undergraduate laboratory in control systems. This study sought to answer the question: what are the most important objectives, concepts, and components of a laboratory apparatus needed to support an undergraduate control systems laboratory? Like Cagiltay et al. (2009), this study used a survey to gather data from control systems faculty. With this data, this study defined a common basis from which future control systems laboratories can be developed and compared.
3.3 Methods

This study included two different types of surveys approved by the Institutional Review Board (IRB #16000). The first survey used a Delphi format, which uses multiple rounds to bring panelists to a consensus on a particular topic Diamond et al. (2014). The follow-up survey was a traditional single round survey. The follow-up survey was shorter so that feedback from a larger portion of the control systems community could be attained. Each survey used the following three questions:

1. What are the most important learning outcomes (e.g. the ability to tune a controller to meet specifications, the ability to implement a specific controller, the ability to communicate results) of your control systems laboratory?

2. What are the most important control systems related concepts for students to learn or be able to demonstrate during a control systems laboratory?

3. What are the most important equipment/tools/software for the students to experience during a control systems laboratory?

3.3.1 Recruitment

For the Delphi survey, the panelists were recruited via fliers at conferences, announcements through American Society of Engineering Education (ASEE) list-servers, social media (e.g., Facebook, Twitter, and LinkedIn), and my personal network. The panel for the Delphi survey consisted of forty faculty members from a variety of program types, disciplines, and institution types.

During December 2015 and January 2016, a second group of survey participants was recruited through a variety of platforms including emails to members of engineering organizations, social media, and word of mouth. Emails or announcements were sent to the following groups: ASEE Engineering Research and Methods Division, ASEE Electrical and Computer Division, ASEE Mechanical Engineering Division, IEEE Control System Society, and ASME Dynamic Systems and Control Division. Whereas the Delphi panelists consisted of only faculty, the follow-up survey participants included both faculty and industry practitioners.
3.3.2 Delphi survey logistics

The Delphi survey consisted of four rounds and was based on a similar survey by Goldman et al. (2010). In round one, panelists listed their ideas for objectives, concepts, and laboratory components in an open response format. The responses were consolidated into the top 15 objectives, 26 concepts, and 15 laboratory components. In round two, panelists rated each of these consolidated items on a 1-10 scale, with one denoting very low importance and ten denoting very high importance. Only whole number ratings were accepted. A rating for each item was required before a panelist could advance to the next group of items. At the end of round two, the mean and interquartile range (IQR) of each item was calculated. (The IQR is also known as the middle 50%.) In round three, panelists were presented with the same items and the same 1-10 scale, but they were also presented the mean and IQR for each item from round two. If they selected a value outside of the IQR, they were required to justify their choice. Finally, in round four the participants were presented with the mean, IQR, and justifications from round three and asked to rate each item again.

The survey for each round was available for two weeks. All four rounds of the survey were administered using the web-based survey tool Qualtrics. The panel feature of Qualtrics was used to track participation and send e-mail reminders for rounds two through four. At least three reminders were sent to each panelist during the two week period.

3.3.3 Follow-up survey logistics

The follow-up survey was used to obtain input from more of the control systems community. The follow-up survey was similar to round two of the Delphi survey. The items were presented with the same wording and order as in the last three rounds of the Delphi survey. However, the follow-up survey did not include any of the statistics or comments from the Delphi survey. To manage the amount of time spent on the survey, participants in the follow-up survey were presented with either the concept group (with only 15 of the concept 26 items to rate) or the laboratory component group. I used the survey flow feature of Qualtrics to manage the number of participants that were presented with either group. The follow-up survey also included a set of demographics questions.
3.4 Results

3.4.1 Panelist and participant demographics

The Delphi panel comprised 40 current and former faculty members. These panelists represented the diversity of control systems education. The Delphi panelists were from all institution types; see Figure 3.1. These institutions included 24 public institutions and 16 private not-for-profit institutions. The follow-up participants were also from all institution types; see Figure 3.1. The 45 follow-up participants represented 27 public institutions, 10 private not-for-profit institutions and 1 private for-profit institution. Additionally, nine participants identified as being primarily a practitioner from a variety of industries. Four of the practitioners had also taught at a university. Two of the panelists and six of the participants were from institutions outside of the United States. The panelists and participants represented a variety of programs; see Figure 3.2. Four institutions were represented in both groups of participants.

![Figure 3.1: Institution type.](image)

All of the panelists participated in at least two of the rounds, and 27 panelists participated in all four rounds. Rounds two, three, and four had participation from 36, 32, and 33 of the panelists, respectively. Not all of the participants in the follow-up survey completed the entire survey. Only submissions that rated at least 12 of the objectives were included in the analysis.

The names of panelists were compared to the names provided in the follow-up survey. Four
persons participated in at least two rounds of the Delphi survey and in the follow-up survey. Three of these persons participated in round four of the Delphi survey, and their submissions were removed from the follow-up data. The fourth duplicate person did not participate in round four; therefore, his submission was included in the follow-up analysis. During the Delphi surveys, there were indications that the emphasis of concepts and the components used in two-year programs were different from four-year programs. For example, one panelist from a community college stated in round three “not what a community college does” for most of the concepts. Therefore, responses from two-year programs were removed from both the Delphi and follow-up survey data before analysis.

3.4.2 Delphi results

First, the descriptive statistics were calculated (e.g., mean, standard deviation, median, IQR, minimum, maximum) for each item and round. The item means and standard deviations from round four are included in Tables 3.2-3.4. The numbers with each item description indicate the original order in which the items were presented in each round.

In order to visualize the data, box and whisker plots with data for each item from rounds two through four were created. The trends of the IQR in rounds two through four were clear from the box plots. In round four, zero was the size of the smallest IQR, and it corresponded to objective
11, *collect and visualize input and output data*; see box plot in Figure 3.3. The size of the largest IQR in round four was four, corresponding to laboratory component 1, *LabVIEW*; see box plot in Figure 3.4.

There are many definitions of consensus for Delphi studies. Diamond et al. (2014) examined 100 Delphi studies and summarized their definitions of consensus. Two common definitions took the form of a minimum percentage at a specific value, or a minimum percentage within a range of values. Among these definitions, the median of these threshold percentages was 75%. Other common definitions took the form of a decreasing IQR, or the central tendencies of the responses. Since there was no prior expectation of the central value for any item in this study, a criterion related to central tendencies (e.g., median greater than 7) was not included. Based on these options and the provided examples, each item was analyzed based on the following criteria:

**Criterion 1.** At least 75% of round four panelists rated the item at the median,

**Criterion 2.** At least 75% of the ratings were within a three point range (e.g., 8-10),

**Criterion 3.** Size of the IQR ≤ 2, and

**Criterion 4.** The IQR decreased or stayed the same from round two to three and from round three to four.

Objective 11, *collect and visualize data*, was the only item that met criterion 1. In round four, 76% of the panelists rated objective 11 at eight (the median). Thirty-six items met criterion two. Forty-six items met criterion three. From rounds two to three, the size of the IQR for each item decreased or stayed the same. Then from round three to four, the size of the IQR for five items increased. Since there is expected variation between programs and institutions, criterion 1 seemed too conservative for this study. Based on the criteria above, the following categories of consensus were defined:

- Consensus: all of criteria 2, 3, and 4 were met;
- Possibly have consensus: two of criteria 2, 3, and 4 were met (P);
- No consensus: none or at most one of criteria 2, 3, and 4 was met (N).

The letter in parenthesis indicates the value in the “C?” column of Tables 3.2-3.4. In total, 33 items achieved consensus, 17 items might have had consensus (P), and 7 items did not have consensus (N).
3.4.2.1 Objectives

The objectives reached the most consensus of all items in the Delphi survey. Eleven of the objectives reached consensus and the remaining four have possibly reached consensus. One of the four objectives that possibly had consensus, *tune a controller* (7) did not satisfy criterion 4, the IQR decreases or stays the same in each Delphi round. However it came close, the IQR went from each round was 1, 1, and 1.25 for rounds 2, 3, and 4, respectively.

The objectives probably had the most consensus because many of them were somewhat generic in wording. For example, objective 5, *design and verify a controller meets specifications*, was independent of the program (e.g., electrical, mechanical, engineering technology). Objective 14, *write a laboratory report that includes topics like design, experimental procedures, results, and analysis*, was also generic. However, in the comments after round three, several panelists mentioned that formal laboratory reports are not a focus of the control systems laboratories at their institution because laboratory reports are an objective of a different laboratory course. This difference in emphasis might have caused some of the ratings to differ and therefore reduce the consensus.

3.4.2.2 Concepts

Over half (16) of the 26 concept items reached consensus. Of the remaining items, six concepts possibly had consensus and four concepts did not have consensus. The six concepts that might
Figure 3.4: Most disagreement: tool 1, LabVIEW.

have reached consensus might vary in priority based on program. For example, concept 16, frequency response, might be less important in an electrical engineering control systems course than a mechanical engineering course. Understanding the frequency response of a system is an important step in some control systems designs. Electrical engineering students are likely to learn about frequency response in a signals and systems course prior to enrolling in a control systems course, whereas mechanical engineering students learn frequency response only in a control systems course. The four concepts that did not achieve consensus depend primarily on the level (e.g., upper-level undergraduate, graduate). For example, observability and observer design (5) is usually only taught in graduate or upper-level undergraduate elective courses, which may not be offered at all of the institutions represented.

3.4.2.3 Laboratory components

Less than half (six) of the 15 laboratory component items reached consensus. Six laboratory components possibly had consensus and three laboratory components did not have consensus. Some components might have reached consensus but because of confusion in the item description or differences in programs, they remained at possible consensus. For example, physical lab bench equipment (10) and virtual or simulated lab bench equipment (11) were separate items to determine whether virtual equipment could be substituted for physical equipment if cost was a constraint. Based on the round three comments, differentiation based of the type of equipment based on budget
was not clear for all panelists. One panelist said,

I’m a big proponent of hardware. Simulation is great, but hardware is ultimately what matters.

as the reason for a high round three rating of physical equipment. Whereas another panelist said,

Virtual tools would be just as good and much less expensive.

as the reason for a low round three rating of physical equipment. Both items possibly reached consensus, but the average rating of virtual equipment is more than 2.5 points lower than physical equipment. Therefore, it is unclear which type of lab bench equipment is preferred in controls laboratories.

Some program (e.g., electrical engineering, mechanical engineering) differences might have caused a wider range of ratings for the type of systems being controlled, e.g., electro-mechanical systems (6), mechanical systems (7), electrical systems (8), and fluid or thermal systems (9). The laboratory components that did not reach consensus (microcontrollers, LabVIEW, and programming languages) might also be program dependent. For example, programming platforms learned in prerequisite courses might limit the hardware or software platforms that can be used in a control systems laboratory, since there may not be enough time to teach the programming language in addition to control systems topics.

3.4.3 Follow-Up survey results

First, the same descriptive statistics for each item were calculated. The follow-up survey item means and standard deviations are also included in Tables 3.2-3.4. In order to determine if the responses in round four and the follow-up survey were similar, a Wilcoxon Rank Sum Test (Bauer, 1972) and the Spearman correlation (Spearman, 2010) were used to compare the mean rating of each group of items. The null hypothesis for the Wilcoxon test is that the distribution of mean rating was the same for round four and the follow-up survey. The null hypothesis of a significance test based on the Spearman correlation is that the ranks of the two populations are not correlated (Zar, 2012). The p-values for each test and Spearman’s $\rho$ are included in Table 3.1. Based on these statistical tests and a significance level of 0.05, the null hypothesis of both tests could not be rejected. Therefore, the relative ratings within each group of items are similar for both round four and the follow-up survey.
Table 3.1: P-Values from Wilcoxon Rank Sum test and Pearson correlation critical value test.

<table>
<thead>
<tr>
<th></th>
<th>Wilcoxon p-value</th>
<th>Spearman p-value</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objectives</td>
<td>0.14</td>
<td>$2.20 \times 10^{-16}$</td>
<td>0.88</td>
</tr>
<tr>
<td>Concepts</td>
<td>0.29</td>
<td>$9.88 \times 10^{-04}$</td>
<td>0.78</td>
</tr>
<tr>
<td>Laboratory Components</td>
<td>0.46</td>
<td>$9.35 \times 10^{-06}$</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Table 3.2: Results from Delphi round four and the follow-up survey for objective items.

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Delphi Round 4 (n=32)</th>
<th>Follow-up (n=45)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10. Connect theory to what is implemented and observed in the laboratory</td>
<td>8.84 0.83</td>
<td>7.91 1.88</td>
</tr>
<tr>
<td>3. Identify differences between models and physical systems</td>
<td>8.38 1.08</td>
<td>7.38 2.06</td>
</tr>
<tr>
<td>5. Design and verify a controller meets specifications</td>
<td>8.28 1.42</td>
<td>8.16 1.61</td>
</tr>
<tr>
<td>1. Model and simulate a system</td>
<td>8.19 1.07</td>
<td>8.20 2.04</td>
</tr>
<tr>
<td>11. Collect and visualize input and output data</td>
<td>8.13 0.65</td>
<td>7.22 2.09</td>
</tr>
<tr>
<td>6. Implement a controller learned in lecture</td>
<td>8.06 1.34</td>
<td>7.78 2.20</td>
</tr>
<tr>
<td>13. Identify practical issues that arise with physical systems such as sensor noise, interference, saturation, and large gains</td>
<td>7.91 0.98</td>
<td>6.91 2.16</td>
</tr>
<tr>
<td>7. Tune a controller</td>
<td>7.75 1.30 P</td>
<td>7.31 2.26</td>
</tr>
<tr>
<td>4. Recognize the tradeoffs between simplifying a system model 7.69 0.95 and being accurate enough to design a controller</td>
<td>6.55 2.33</td>
<td></td>
</tr>
<tr>
<td>2. Perform system identification using data obtained in the laboratory</td>
<td>7.47 1.20</td>
<td>6.39 2.67</td>
</tr>
<tr>
<td>12. Find errors and correct for them (debugging)</td>
<td>6.94 1.06 P</td>
<td>6.38 2.38</td>
</tr>
<tr>
<td>14. Write a laboratory report that includes topics like design, 6.75 1.56 experimental procedures, results, and analysis</td>
<td>P 6.76 2.36</td>
<td></td>
</tr>
<tr>
<td>9. Compare controllers and select the appropriate controller for 6.44 1.34 the provided system</td>
<td>6.84 2.16</td>
<td></td>
</tr>
<tr>
<td>8. Tune a controller while it is running</td>
<td>6.09 1.35 P</td>
<td>5.27 2.91</td>
</tr>
<tr>
<td>15. Design laboratories and do undergraduate research</td>
<td>3.91 1.23</td>
<td>4.56 2.92</td>
</tr>
</tbody>
</table>

3.4.4 Most important items

Each group of items was sorted based on the mean rating from highest to lowest in round four and then the follow-up survey. Tables 3.2-3.4 are sorted by the mean from round four. After sorting
Table 3.3: Results from Delphi round four and the follow-up survey for concept items.

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Delphi Round 4 (n=32)</th>
<th>Follow-up (n=19)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>22. Block diagram representation of a system</td>
<td>9.19</td>
<td>0.59</td>
</tr>
<tr>
<td>21. Transfer functions</td>
<td>9.16</td>
<td>0.68</td>
</tr>
<tr>
<td>24. Stability</td>
<td>8.77</td>
<td>0.61</td>
</tr>
<tr>
<td>19. Step response</td>
<td>8.71</td>
<td>0.85</td>
</tr>
<tr>
<td>20. Laplace transforms</td>
<td>8.45</td>
<td>0.66</td>
</tr>
<tr>
<td>2. PID Control</td>
<td>8.35</td>
<td>0.82</td>
</tr>
<tr>
<td>17. Maximum overshoot or percent overshoot, rise time, settling time,</td>
<td>8.16</td>
<td>0.99</td>
</tr>
<tr>
<td>and steady-state error</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18. Damping ratio and undamped natural frequency</td>
<td>8.03</td>
<td>0.93</td>
</tr>
<tr>
<td>1. Closed loop vs. open loop control</td>
<td>7.97</td>
<td>0.86</td>
</tr>
<tr>
<td>13. Bode plot</td>
<td>7.84</td>
<td>0.92</td>
</tr>
<tr>
<td>16. Frequency response</td>
<td>7.65</td>
<td>1.58</td>
</tr>
<tr>
<td>11. Pole/Zero plots</td>
<td>7.58</td>
<td>1.26</td>
</tr>
<tr>
<td>4. Tracking and disturbance rejection</td>
<td>7.32</td>
<td>1.35</td>
</tr>
<tr>
<td>12. Root locus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Continuous-time</td>
<td>7.16</td>
<td>1.22</td>
</tr>
<tr>
<td>3. Compensators including lead and/or lag control</td>
<td>6.87</td>
<td>1.21</td>
</tr>
<tr>
<td>25. System order reductions and other modeling approximations,</td>
<td>6.52</td>
<td>1.54</td>
</tr>
<tr>
<td>such as only using dominate poles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26. Nonlinear characteristics, such as the effects of friction</td>
<td>6.52</td>
<td>1.90</td>
</tr>
<tr>
<td>15. Phase and gain margins, phase and gain crossover frequencies</td>
<td>6.42</td>
<td>1.74</td>
</tr>
<tr>
<td>14. Bandwidth, peak value, and peak frequency</td>
<td>6.35</td>
<td>1.54</td>
</tr>
<tr>
<td>23. State-space</td>
<td>5.84</td>
<td>1.99</td>
</tr>
<tr>
<td>10. Discrete-time</td>
<td>4.97</td>
<td>1.73</td>
</tr>
<tr>
<td>5. Observability and observer design</td>
<td>4.35</td>
<td>1.84</td>
</tr>
<tr>
<td>7. Ziegler-Nichols</td>
<td>3.42</td>
<td>2.01</td>
</tr>
<tr>
<td>8. Ladder logic</td>
<td>3.03</td>
<td>2.16</td>
</tr>
<tr>
<td>6. Adaptive control</td>
<td>2.58</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Each group by mean, the order was compared to determine which items appeared in approximately the same order in both round four and the follow-up survey. I sorted by mean in order break ties that existed when sorting by median. While the specific order was slightly different for each survey,
Table 3.4: Results from Delphi round four and the follow-up survey for laboratory component items.

<table>
<thead>
<tr>
<th>Laboratory Components</th>
<th>Delphi Round 4 (n=32)</th>
<th>Follow-up (n=22)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Mathworks including MATLAB, Simulink, SISO Tool, and QUARK</td>
<td>8.68 0.82</td>
<td>8.14 1.58</td>
</tr>
<tr>
<td>6. Electro-Mechanical systems including servos or motors</td>
<td>8.23 1.01</td>
<td>7.14 2.34</td>
</tr>
<tr>
<td>7. Mechanical systems including spring-mass-damper, actuators, or hydraulics</td>
<td>7.94 1.27</td>
<td>6.91 2.39</td>
</tr>
<tr>
<td>13. Tools representative of industry</td>
<td>7.55 0.71</td>
<td>6.00 2.92</td>
</tr>
<tr>
<td>8. Electrical systems including first and second order circuits</td>
<td>7.42 1.01</td>
<td>6.23 2.61</td>
</tr>
<tr>
<td>12. Data acquisition</td>
<td>7.32 1.30</td>
<td>7.14 2.42</td>
</tr>
<tr>
<td>14. Digital and analog I/O</td>
<td>7.19 0.86</td>
<td>6.50 2.62</td>
</tr>
<tr>
<td>10. Physical lab bench equipment including power supply, function generator, multimeter, oscilloscope, spectrum analyzer</td>
<td>6.97 1.76</td>
<td>6.18 2.42</td>
</tr>
<tr>
<td>15. A/D and D/A conversion</td>
<td>6.29 1.61</td>
<td>6.27 2.72</td>
</tr>
<tr>
<td>4. Microcontrollers including Arduino or embedded systems</td>
<td>5.68 2.04</td>
<td>5.45 2.71</td>
</tr>
<tr>
<td>9. Fluid or thermal systems including temperature or liquid level in tanks</td>
<td>5.32 1.53</td>
<td>5.64 2.37</td>
</tr>
<tr>
<td>11. Virtual or simulated lab bench equipment including power supply, function generator, multimeter, oscilloscope, spectrum analyzer</td>
<td>4.32 1.63</td>
<td>5.41 2.50</td>
</tr>
<tr>
<td>1. LabVIEW</td>
<td>4.06 2.02</td>
<td>5.41 2.76</td>
</tr>
<tr>
<td>3. Programming languages including C and Python</td>
<td>4.06 2.17</td>
<td>4.09 2.71</td>
</tr>
<tr>
<td>5. Programmable logic controllers (PLCs)</td>
<td>3.42 2.21</td>
<td>4.36 3.13</td>
</tr>
</tbody>
</table>

there was a clear separation of items in the objective and laboratory component groups.

3.4.4.1 Objectives

For the objectives group, the top eight items were the same in round four and the follow-up survey. However, the order was slightly different. Figure 3.5 illustrates how the ranked order of objectives in round four mapped to the ranked order of objectives in the follow-up survey. In Figure 3.5, the blue squares are arranged in the rank order from Delphi round four survey and the orange circles are arranged in the rank order from the follow-up survey. There was only one place in the list of objectives where a line could be drawn that created two subsets of the same items. This separation
occurred after the top eight items. Therefore, I identified eight highest ranked objectives as the most important objectives for control systems laboratories. Seven of the eight highest ranked items also achieved consensus in the Delphi study. The double line in Figure 3.5 and Table 3.2 separates the eight most important objectives from the rest.

Figure 3.5: Comparison of the ranked order of objectives in round four versus the follow-up surveys.

3.4.4.2 Concepts

For the concepts group the order of items was significantly different between round four and the follow-up survey. The order of the concepts could be significantly different because over a third of the Delphi panelists were mechanical engineers, while over a third of the follow-up participants were electrical engineers. Another reason for the difference could be that only 15 of the 26 items were used in the follow-up survey, therefore the relative scores might be different. In addition, only 19 follow-up participants were asked to rate the concept items.

In Figure 3.6, the blue squares are arranged in the rank order from Delphi round four survey and the orange circles are arranged in the rank order from the follow-up survey. A line of separation similar to the objectives could be drawn between tracking and disturbance rejection (4) and continuous-time (9). Therefore, I identified the top 13 concepts as the most important concepts. The double line in Figure 3.6 and Table 3.3 separates the most important concepts from the rest.
3.4.4.3 Laboratory components

The order of the laboratory component items for round four and the follow-up survey was compared using the corresponding illustration of rank order. The nine highest rated laboratory components were the same for both round four and the follow-up survey. The highest two laboratory components *MathWorks* (2) and *electro-mechanical systems* (6) were the highest two in both surveys. The rest of the nine highest rated items appeared in a slightly different order, see Figure 3.7. In Figure 3.7, the blue squares are arranged in the rank order from Delphi round four survey and the orange circles are arranged in the rank order from the follow-up survey. Six of the nine highest rated items achieved consensus and the other three had a possible consensus in the Delphi study. Therefore, I
ranked the nine highest ranked items as the most important laboratory components. The double line in Table 3.4 separates the nine most important laboratory components from the rest.

![Figure 3.7: Comparison of the ranked order of components in round four versus the follow-up surveys.](image)

3.4.5 Limitations

The results of this study might have been affected by the characteristics of the panelists and participants. Four-year engineering programs in the United States dominated the panel and the follow-up survey. There are some indications that control systems laboratories for some engineering technology programs at community college differ from the four-year engineering programs. However, there were not enough panelists or participants from community colleges to make this distinction definitively.

To limit the length of the follow-up survey, participants were asked to rate only the concept items or only the laboratory component items. This decision led to lower sample sizes. In addition, in the follow-up survey only 15 of the 26 concepts were presented to participants to limit the time commitment. The shortened list could have skewed the ratings lower because the concepts that the panelists rated very low, like adaptive control, were not present in the follow-up survey.

There was also some confusion about some of the items in the survey. Based on comments in round three there seems to have been confusion in the difference between objectives design and...
verify a controller meets specifications (5), implement a controller learned in lecture (6), and tune a controller (7). Such confusion was highlighted by one panelist that said,

If they design and implement a controller that meets the specifications, I would say they have ‘tuned it’. I understood the design to be an iterative process, but perhaps that’s what you meant by ‘tune’.

as the reason for a low rating for objective seven. Whereas another panelist stated,

It is not really useful to implement a control system without tuning it to understanding how gains impact the controller’s performance. For example, implementing a PID controller without learning how to tune it isn’t very useful.

as the reason for their high rating for objective seven. In future work, clearer descriptions of some items could be helpful.

3.5 Discussion

Items from this survey overlap with experiments listed in Dorato (1990) and objectives listed in Antsaklis et al. (1999). Of the experiments listed in Dorato (1990), four were covered by items in this survey and three were not. In addition, two of the items covered on this survey also made the most important items list. The following is a list of these experiments with the corresponding item in parenthesis and an asterisk to indicate an item was identified as one of the most important objectives or components:

- “DC position/velocity servo” (laboratory component 6*),
- “system modeling” (objective 1*),
- “lead/lag compensation” (concept 3),
- “digital control” (concept 10),
- “analog computer simulation,”
- “computer-aided design,”
- “optimal control.”
Given the changes in technology since 1988, it is possible that items from this survey such as MathWorks (laboratory component 2*) and model and simulate a system (objective 1*) are the modern equivalent of “computer-aided design.”

Of the objectives listed in Antsaklis et al. (1999) four of the objectives overlap with items in this study, two objectives are partially covered, and one is not covered. The following is a list of the objectives from Antsaklis et al. (1999) with the corresponding item in parenthesis and an asterisk to indicate an item was identified as one of the most important objectives or components:

- demonstrate analytical concepts (objective 10*);
- introduce real-world issues like noise, saturation, and uncertainty (objective 13*);
- provide instrumentation and measurement (objective 11* and components 10*, 11, and 12*);
- exposure to broader design constraints (partially covered by objectives 3*, 5*, and 9);
- maintain engineering notebooks and write report (objective 14*);
- problem solving and team work (first part covered by objective 12*);
- provide teaching experience for graduate assistants.

While the field of control systems has changed since these previous surveys, some of the laboratory objectives have remained the same. This study identified current trends of control systems laboratories and also added additional details that were not addressed in previous studies, like specific components used in the laboratory.

This study expanded upon previous information about control systems courses and laboratories. I drew upon faculty and industry professionals across the diversity of control systems to create a framework for developing control systems laboratories. My framework includes the most important objectives, concepts, and components of a laboratory apparatus for a control systems laboratory. Because of the diversity and differences between the disciplines that teach control systems, this framework is provided as a guide rather than a prescriptive set of instructions. Instructors may select from the items on each list to develop an effective laboratory experience for their students, but are encouraged to explain the rationale for which items were selected when sharing their laboratory experience with other instructors.
3.6 Conclusions and future work

Based on the results of this study, a panel of control systems faculty has come to consensus ratings in the following areas:

- 11 of the 15 learning objectives identified,
- 16 of the 26 concepts identified, and
- 6 of the 15 components of a laboratory apparatus identified.

This study has also provided a list of the eight most important learning objectives, thirteen most important concepts, and nine most important components of a laboratory apparatus. Based on this information, a common framework for undergraduate control systems laboratory development has been defined. The framework defined in this paper is more detailed than previous information provided about control systems courses Antsaklis et al. (1999); Dorato (1990) and includes the most recent technology that is currently being used in control systems laboratories. The framework was developed as a guide rather than prescriptive set of instructions, therefore instructors may select from the items on each list to develop an effective laboratory experience for their students. Additionally, the framework can be referenced when documenting laboratory experiences.

With more data, it would be helpful to determine if more detail could be added to this framework based on specific four-year programs (mechanical versus electrical) and two-year programs. This framework can be used to develop and compare laboratories. An example of a comparison based on this framework is to identify low-cost hardware to use in control systems laboratories. A website with this low-cost hardware comparison is planned.
CHAPTER 4

BUILDING PROJECT MANAGEMENT CAPABILITY THROUGH AN IMMERSIVE PRACTICAL EXPERIENCE

4.1 Introduction

Undergraduate engineering students have multiple opportunities to complete laboratory experiments and projects in their technical courses. Laboratories and experiments are a form of experiential learning, a process by which a student creates knowledge through the insights gained from an experience (Kolb, 2014). Experiential learning has become the standard for many courses in STEM, and the benefits have been well documented (Kolb, 2014).

Experiential learning can be incorporated not only in technical courses but also in leadership and management courses (Guthrie & Jones, 2012). Most examples of experiential learning in leadership include case studies, observations, and simulations. Leadership experiences can be provided by team projects, but these teams are typically made up of students solely in the management courses, so not all of the students gain experience as leaders. Another option would be to coordinate two separate experiences: one for project managers and one for team members; this option allows all students interested in the project management to practice leading students interested in completing an extensive project. Each group of students (project managers and team members) has two different sets of learning objectives. This chapter examines a project management program with this design and describes the experiences of a project manager in the program.

4.2 Background

This chapter describes a two-course model as a possible form of experiential learning for project managers. The two-course model allows for students in the project management course to gain experience as project managers in a learning environment similar to other engineering laboratories.
4.2.1 Project management

The Project Management Institute (PMI) was founded in 1969 (Project Management Institute [PMI], 2016). It has become the global professional organization for project managers and set the industry standards for project managers (Garel, 2013). PMI has issued over 500,000 certifications in 180 countries around the world (PMI, 2015). PMI (2013) defines a project manager as the person designated to achieve the project goals. The project manager plays a key role in the success of a project (Anantatmula, 2010).

PMI (2013) defines three multi-faceted areas of project management: process groups, knowledge areas, and interpersonal skills. The process groups are initiating, planning, executing, monitoring and controlling, and closing. The knowledge areas are project integration management, project scope management, project time management, project cost management, project quality management, project human resource management, project communications management, project risk management, project procurement management, and project stakeholder management. The interpersonal skills are leadership, team building, motivation, communication, influencing, decision making, political and cultural awareness, negotiation, trust building, conflict management, and coaching (PMI, 2013).

4.2.2 Experiential learning

Since Kolb (2014) introduced the experiential learning model in 1978, hundreds of studies have been published across all disciplines including management. Kolb’s cycle of experiential learning is illustrated in Figure 4.1. In the model, there are four modes of experiential learning: (1) concrete experience, (2) reflective observation, (3) abstract conceptualization, and (4) active experimentation. For a concrete experience, a student should have an open mind and be immersed in the situation. Then, for reflective observation, they should reflect on the experience from multiple perspectives. Next, in abstract conceptualization, they should turn their observations into concepts and theories. Finally, for active experimentation, they should use the new theories to solve problems or make decisions. Students may enter the cycle at any point, but need to experience all four modes.
4.2.3 Experiential learning in project management

Portz (2014) stressed the value of projects in the classroom because it provides an authentic real-world experience. Several examples of experiential learning for leadership are described in the literature. Guthrie & Jones (2012) suggested observation of leaders and case studies. In this process, they emphasized the importance of reflective observation through both written reflection and class discussion. In a research methods course for an organizational leadership program, Bangs (2011) described incorporating all four of Kolb’s modes of experiential learning into the research process. Chen & Chuang (2009) described a project management course designed for experiential learning. Because the teams are made up of students in the same course, not all of them have the opportunity to be project managers themselves, however. Computer simulations are also used as a form experiential learning in leadership courses (Siewiorek et al., 2012). In the simulation studied by Siewiorek et al. (2012), the simulation covered only business processes and decision making. Gamble & Davis (2002) implemented another option: two separate courses. In the FIST program there was one course for graduate students in project management and one course for undergraduate students, primarily software engineering students (Gamble & Davis, 2002). In these concurrent courses, graduate students in the project management course learned about project management and led a team of students in the undergraduate course, while the undergraduates learned about software development and completed the work on the project (Gamble & Davis, 2002).

In each of these examples, part of Kolb’s cycle or the project management experience is missing. In the observations Guthrie & Jones (2012) suggested, the project management students are not experiencing the role of the leader, they are observers. As observers, students do not have the opportunity for active experimentation modes of Kolb’s cycle. In Bangs (2011) course, students
experience all of Kolb’s cycle as researchers not as leaders. While Chen & Chuang (2009) designed a course for Kolb’s cycle around project implementation, since there is only one course not all students in the course have the opportunity to serve in the role as project manager for the entire semester. Siewiorek et al. (2012) described a simulation of project management. In the simulation all students have the chance to practice some project management skills, however since all of the people are also simulated there is not an opportunity to practice interpersonal skills. Finally, Gamble & Davis (2002) implemented a two course model that provides students in a project management course the opportunity to lead a team of undergraduates for the entire semester. However, the enrollment in the project management course was not balanced with the number of undergraduate teams. Therefore, some students may end up being assigned as a supervisor of project managers for the semester. While a supervisor of project manager needs many of the same skills as a project manager it would not create the same experience for both the supervisor and project managers.

4.3 Purpose

The purpose of this study is two-fold. First, this ethnographic study investigates two concurrent project-based courses: one for project managers and one for undergraduate team members. The focus of this study is the experience of a project manager in the project management course. Second, this study provides an example of the implementation of a two concurrent project-based courses and recommendations for organizing a similar pair of concurrent courses at another university.

I selected this study because I felt unprepared for my role as a project manager in industry. I would have appreciated a similar opportunity to practice being a project manager and reflect on the experience prior to taking the role in industry.

4.4 Method

For this study, I selected autoethnography as the method, because I planned to enroll in the project management course and draw primarily from my own experiences rather than the experiences of other project managers in the course or student team members. According to Glesne (2006), autoethnography is used to describe a culture and is produced by a member of the culture and the writer interjects personal experience. There several differences between an autoethnography and an ethnography with a participant observer. In an autoethnography, the researcher’s experience
is the primary source of data (Ellis, 2004) whereas when the researcher is a participant observer, the data are primarily drawn from others (Glesne, 2006). In an autoethnography, the results focus on the narratives and feelings of the author’s experiences (Sochacka et al., 2016). As a participant observer, the author is recording how groups or individuals within an organization interact (Winklhofer, 2002). Additionally, as a participant observer, the author may contribute as a member of the organization in order to minimize the impact of their presence; however, the author’s experience is not the focus of the results (Winklhofer, 2002). While autoethnographic and ethnographic methods are both becoming more popular, there are few examples of either in project management research (Spurlock et al., 2015).

I gathered the primary data using an autoethnographic method. The culture examined in this chapter is project management experience in a graduate course for project managers. Furthermore, I used the five features of analytic autoethnography: (1) complete member researcher status; (2) analytic reflexivity; (3) narrative visibility of the researcher’s self; (4) dialogue with informants beyond the self; and (5) commitment to theoretical analysis (Anderson, 2006). As project management student, I was completely immersed in the experience of being a project manager and played a major role in the stories included in this chapter, the criteria for features (1) and (3). Analytic reflexivity (2) refers to the analysis of the impact on the members of the culture and on the researcher as a result of the study. I had extensive dialogue with informants (4) throughout the semester and during the interviews conducted with other project managers in the following semester. Finally, for the commitment to theoretical analysis (5). I analyzed the experience to illustrate how it relates to my conceptual framework. For project management conceptual framework, I used the process groups, knowledge areas, and interpersonal skills described in the Guide to the Project Management Book of Knowledge (PMBOK) (PMI, 2013). I selected Kolb’s model (Kolb, 2014) as the experiential learning conceptual framework for analysis.

4.4.1 Context of the study

Project Experience Courses (PEC) is a program within the College of Engineering at the study site. The program includes one undergraduate course, titled Learning Through Projects (LTP), and one graduate course, titled Applied Project Management (APM). Both courses are open to students enrolled in any major. The LTP course has several sections, and each sections students comprise a project team. Each LTP team was led by a pair of students from the APM course for the duration
of the 15-week semester. Together the APM project managers and a team of LTP students define and deliver a product that meets the needs of their client before the end of the semester. PEC, LTP, and APM are all pseudonyms for the actual program and courses at the study site.

In the spring of 2015, I enrolled in the APM course. APM students were called PEC project managers (PMs). Throughout the semester I was a PEC PM, I took notes in class, wrote journals, and reflected on my interactions with members of the student team. Prior to being a PEC PM, I was a project manager in the aerospace industry for over four years. I drew upon both experiences for this autoethnography research project. Then I compared my experience as a PEC PM to my conceptual frameworks: PMBOK and Kolb’s cycle of experiential learning.

4.4.2 Research validation

In order to validate my research method, I considered each of the five categories of validation created by Walther et al. (2013): theoretical validation, procedural validation, communicative validation, pragmatic validation, and process reliability. Within each category the research should consider both creating the data and handling the data. For each of these five validation categories, provided a set of questions for researchers to consider. For each of these five validation categories, Walther and Sochacka (2014) provided a set of questions for researchers to consider. I worked through each category of questions. The autoethnographic method increased the validity in some categories and threatened the validity in other categories. I will explain each of the five areas in detail in the following paragraphs.

4.4.2.1 Theoretical validation

Theoretical validation determines if the knowledge produced corresponds to the observed culture (Walther et al., 2013). First, I asked, “How will I be able to see the full extent of this social reality?” (Walther & Sochacka, 2014). I enrolled in the course for credit as part of my graduate program in systems engineering, therefore I was participating in the course under similar circumstances as other PEC PMs. The next question I asked was, “What could prevent me from seeing the full extent of this social reality?” (Walther & Sochacka, 2014). One possible influence to the social reality is the potential that other project managers or team members might alter their interactions with me if they knew the study was being conducted. Therefore, I did not tell anyone during the semester I was enrolled in APM that I was documenting my experiment for this study. Additionally, my
personal experiences influenced how I reacted and analyzed events in PEC. Therefore, I asked each PEC PM that was interviewed to read a draft of the narratives and confirm that I had accurately captured and arrived at a plausible interpretation of the experience.

4.4.2.2 Procedural validation

Procedural validation suggests features to be added in order to improve the fit between the knowledge produced and the observed culture (Walther et al., 2013). In this category, I asked myself, “What features can we build into the inquiry to mitigate threats to an authentic view of the social reality?” (Walther & Sochacka, 2014). I included triangulation data beyond by own experience by interviewing four other PMs with different backgrounds; see Table 4.1. Three of the PMs I interviewed were PEC PMs in a different semester. My co-PM was the fourth PM interviewed in this study. All of the interviews were conducted after I completed my semester as a PM. Another question I asked was, “What features can we design into our process of interpretation to mitigate the risk of mis-constructing the social reality of our participants?” (Walther & Sochacka, 2014). When analyzing the data, I compared my experience to the other PMs and existing literature about project management and learning. Also, as stated in the previous category, I asked each interviewed PEC PM to review a draft of the interpretation of their experiences.

Table 4.1: PM participant demographics.

<table>
<thead>
<tr>
<th>PM</th>
<th>Gender</th>
<th>Semester in APM</th>
<th>Status In School</th>
<th>Work Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panther</td>
<td>Female</td>
<td>Fall 2013</td>
<td>Master’s</td>
<td>2 years</td>
</tr>
<tr>
<td>Lily</td>
<td>Female</td>
<td>Fall 2013</td>
<td>Master’s</td>
<td>None</td>
</tr>
<tr>
<td>James</td>
<td>Male</td>
<td>Fall 2014</td>
<td>Master’s</td>
<td>More than 10 years</td>
</tr>
<tr>
<td>Margaret (my co-PM)</td>
<td>Female</td>
<td>Spring 2015</td>
<td>Undergraduate</td>
<td>None</td>
</tr>
<tr>
<td>Rebecca (Me)</td>
<td>Female</td>
<td>Spring 2015</td>
<td>Ph.D.</td>
<td>8 years</td>
</tr>
</tbody>
</table>

4.4.2.3 Communicative validation

Communicative validation explains the knowledge creation within the observed culture and the research community (Walther et al., 2013). First, I asked “How can I authentically co-construct meaning of participants’ social realities on their own terms” (Walther & Sochacka, 2014). This is where authoethnography has an advantage over ethnography. Since I was writing about my own
experience, my own voice and terms were included. While writing each narrative, I consulted my field notes, APM assignments, email archives, and PEC handouts to ensure the completeness of each account. Then I asked, “How can I construct my findings within the meaning conventions of the relevant research community?” (Walther & Sochacka, 2014). After my semester as a PEC PM, I presented a preliminary version of the experience at the 2015 American Society for Engineering Management (ASEM) Annual Conference. The paper I submitted was subject to double blind peer review and then presented to an audience of engineering management educators for feedback during the conference.

4.4.2.4 Pragmatic validation

Pragmatic validation explores how well the knowledge created relates to the observed culture (Walther et al., 2013). In this category, I asked, “What theoretical assumptions do we make about the nature of the reality under investigation?” (Walther & Sochacka, 2014). When enrolling in the APM course I assumed that experiential learning was an effective way for students to learn to be project managers and gain transferable skills for industry positions. From my experience in industry, I also had an assumption of what tasks and skills were required of project managers. I also asked, “How meaningful are my interpretations for the social reality under investigation?” (Walther & Sochacka, 2014). As I did not find many examples of this concurrent course structure in the literature, I believe this study adds variety to the options available to instructors to teach project management.

4.4.2.5 Process reliability

Process reliability adds strategies to ensure the research process is resistant to random influences that could impact the data or interpretation (Walther et al., 2013). The first question I asked was, “How can we document and authentically demonstrate the dependability of our entire process of investigation?” (Walther & Sochacka, 2014). All members who assisted in data collection of this study were trained to conduct human subject research. The process for data collection, documentation, analysis, and publication was documented. Then, Institutional Review Board (IRB #16384) approval was obtained for this project. After that I asked, “How can I mitigate, as far as possible, random influences on our process of seeing the social reality under investigation?” (Walther & Sochacka, 2014). I enrolled in APM for the entire semester, so I was able to experience
all aspects of the course. Unfortunately, due to personal conflicts, I was unable to attend two of fifteen class sessions of the APM course and one of 31 class sessions of LTP course. Through the other PMs I interviewed, I was able to obtain four additional perspectives. However, I was able to only recruit PMs who were domestic students to participate in the interviews. In the semester I enrolled in APM, there were at least three PMs who originated from outside the United States and that perspective was not captured in this study. Each PM provided informed consent prior to the start of the audio recorded interview. The interview questions used in all four interviews are included in Appendix C. I conducted three of the PM interviews in person. Then, I trained an experienced education researcher on the interview process. He conducted the interview of my co-PM via Skype. I asked him to conduct the interview of my co-PM so that I would not influence her recollection of her experience. He used Skype for the interview because it was conducted over a semester break. After the interview was complete, he sent me the audio recording and completed forms. To ensure anonymity, I assigned pseudonyms to all participants, the university, the program, and the related organizations. I also transcribed all interviews using pseudonyms and then deleted the audio recording. Through the analysis of the PEC PM experience and related literature, I explored the limits of transferability which are described later in the Limitations section.

4.4.2.6 Additional Considerations

In autoethnographic research, it is important for the researcher to have self-awareness of his or her impact to the study (Anderson, 2006). At the time I enrolled in APM, I already had experience with each of the roles undertaken by a PEC PM: student, project manager, and teacher. When I started APM, I was in the middle of my second year as a doctoral student in systems engineering and I had already completed Master of Science and Bachelor of Science degrees in electrical engineering. I completed a project management course to fulfill part of the requirements of my master’s degree and I completed numerous professional development courses on leadership and other interpersonal skills. For four years, I worked as a project manager in the aerospace industry. During my time in industry, I led four different project teams and participated in all phases of the project life cycle. Additionally, I completed my university’s required teaching assistant training and a college teaching course before enrolling in APM. Therefore, I had significantly more relevant prior experience than most of the other APM students.
4.5 Results and Discussion

I started by capturing my detailed accounts of key events and assignments while I was a PEC PM. Then, I analyzed the experiences based on the conceptual framework, the PMBOK, and compared them to my experience in industry. Finally, I compared my experiences with those of other PMs that were interviewed. Overall, the PEC PM experience has evolved to become a comprehensive learning experience for PMs in the course.

4.5.1 Course organization and roles

In the spring semester of 2015, there was one section of APM and 10 sections of LTP. The APM course met on Fridays from 10:00 to 11:50 am. Two students from APM (co-PMs) led one section of LTP. My Co-PM was Margaret, a senior undergraduate majoring in engineering. The students enrolled in one LTP section formed one project team. Each LTP section had a maximum enrollment of 15 students; our section had nine students and met from 9:30 to 10:50 am on Tuesdays and Thursdays. Our LTP section was diverse, see Table 4.2 for details. Each section of LTP had one client. During the semester, the team, Margaret, and I defined a project with multiple deliverables. While LTP sections in previous semesters worked with the same client, we had our own distinct project that was not a continuation of any previous projects. At the end of the semester, we delivered the project to our client.

<table>
<thead>
<tr>
<th>Pseudonym</th>
<th>Class Standing</th>
<th>Major</th>
<th>Gender</th>
<th>Domestic vs. International</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mike</td>
<td>Senior</td>
<td>Civil Engineering</td>
<td>Male</td>
<td>Domestic</td>
</tr>
<tr>
<td>Brandon</td>
<td>Freshman</td>
<td>Engineering Physics</td>
<td>Male</td>
<td>Domestic</td>
</tr>
<tr>
<td>Noah</td>
<td>Senior</td>
<td>Communications</td>
<td>Male</td>
<td>Domestic</td>
</tr>
<tr>
<td>Luke</td>
<td>Junior</td>
<td>Communications</td>
<td>Male</td>
<td>Domestic</td>
</tr>
<tr>
<td>Ray</td>
<td>Senior</td>
<td>Industrial Engineering</td>
<td>Male</td>
<td>International</td>
</tr>
<tr>
<td>Emma</td>
<td>Freshman</td>
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<td>Female</td>
<td>Domestic</td>
</tr>
<tr>
<td>Isabella</td>
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<td>Female</td>
<td>Domestic</td>
</tr>
<tr>
<td>Drew</td>
<td>Sophomore</td>
<td>Physics</td>
<td>Male</td>
<td>Domestic</td>
</tr>
<tr>
<td>Brian</td>
<td>Junior</td>
<td>Economics</td>
<td>Male</td>
<td>Domestic</td>
</tr>
</tbody>
</table>

Wendy, the program director, and Sam, the program assistant, organized the PEC program.
Wendy interviewed each prospective APM student who had submitted an application to be a PEC PM. Once Wendy and Sam had reviewed the applications and interviews, they permitted the PMs to enroll in APM. Wendy and Sam also taught the APM course and provided feedback and grades to the PMs throughout the semester. They were responsible for finding and maintaining relationships with client for each team. They held office hours and were available to any PM or team member who needed help throughout the semester. Figure 4.2 illustrates the organizational chart of the PEC program.

![PEC organizational chart](image)

**Figure 4.2: PEC organizational chart.**

Each team worked directly with a real client. Our client, Adam, was the director of a local park. Consistent communication with Adam was important to our success. Throughout the semester, we listened to the priorities and feedback he provided. We ensured that what he said was incorporated in the final deliverables. At times, we were frustrated with Adam because he was not always prompt in providing the data we requested or in some cases could not find the requested data. For example, we asked for the roof square footage of some of the buildings at the park. Unfortunately, he was not able to produce this data so we got creative and estimated the square footage by looking at the buildings on Google maps satellite pictures. There was also misunderstanding between Adam and the team about where rainwater runoff went at the park. Despite these difficulties, Adam was very pleased with the efforts of the team. He appreciated that the team made more than one trip to the park and that the team’s “deliverables are amazing and are going to be so useful as we move forward.” At the end of the semester, he said the “team did an amazing job.” This very positive feedback was reassuring for Margaret and me. For me, it made all of the work of the semester worth it.
4.5.1.1 Analysis and reflection

As PMs, we had multiple roles: project manager, instructor, grader, and student. As project managers, we were responsible for stakeholder management, quality control, and on-time delivery of the project. As instructors and graders, we were responsible for ensuring that the undergraduates achieved the objectives of their course. As students in the APM course, we learned about teaching practices, quality control, leadership skills, and team building techniques. In the LTP classroom, the first three roles overlapped quite a bit. At some points, it was hard for the team to understand how we differed from teaching assistants they had in other courses. We thought we had clarified our role at the beginning of the semester. However, when we asked for anonymous feedback in week seven, one student said, “bigger divide between lecturer and project member.” This statement made us wonder if there was confusion about our role as PMs.

Wendy, Sam, and Adam were our primary stakeholders for the project; however, the College of Engineering and university were also stakeholders because they provided some of the resources necessary to sustain the PEC program. The teams and PMs were also representatives of PEC and the university, therefore our actions reflected upon their reputation. I feel that having stakeholders beyond Wendy and Sam (the instructors providing PM grades) provided an extra layer of reality to the experience. For example, I knew that I would be disappointing Adam if we did not provide quality deliverables at the end of the semester. Therefore, when I was really busy in the middle of the semester, I still placed priory on my PEC responsibilities so that the quality of the project was not impacted. If our project was just submitted for a grade and not to an external client, I may not have placed the same priority on my PEC responsibilities during the semester. I am happy we were able to work together to provide quality deliverables to Adam at the end of the semester.

The organization of PEC allowed each PM the opportunity to practice stakeholder and communications management, both knowledge areas in the PMBOK (2013). In addition, we practiced communication skills and built trust during our interactions with Wendy, Sam, and Adam. Communication and trust building are both interpersonal skills in the PMBOK (2013).

4.5.2 Course timeline

The course timeline paralleled the process groups in the PMBOK (2013). Figure 4.3 summarizes the timeline of the semester.

During the week before the semester started, we spent two and a half days in training learning
the basics of being a project manager, planning for the LTP course, and practicing activities for
the LTP course. On the last day, we gave an 8-minute lesson to a small group of APM students.
The lesson was also video recorded so we could watch a replay with one of the PEC staff later. The
content of the APM course was similar to the pre-semester training just adapted for the phase of
the project or other events in the semester.

Margaret and I initiated the project for our LTP section in the first week by meeting the team
and learning their backgrounds. We also met with Adam and Wendy in the campus’s student
center. In this initial meeting, we discussed the needs of the park that Adam directed, what PEC
projects had been completed in the past, and expectations for this semester. In the second week
of the semester, the students also met Adam.

The team, Margaret, and I spent weeks three through eight on planning. We learned about
the park and staff including their needs and wants. Then we did some initial research on possible
deliverables. We documented the work from the planning phase in the Project Charter, a PEC
assignment submitted by the team with significant input from the PMs. The Project Charter
included the following sections: executive summary; introduction to the partner and issues; problem
statement and project justification; project scope, objectives, and proposed work; work breakdown
structure; outputs and community impact; analysis of safety, environmental, and ethical issues; and
schedule and budget estimate. The work breakdown structure (WBS) documented the sub-tasks
of each deliverable, but it was much simpler than any WBS I had encountered in industry. The
outputs and their impact on the community was identified through logic models. The logic models
developed in class were based on a guide from the W. K. Kellogg Foundation (2004). The Project
Charter contained SMART goals for the project. In this class, we defined the SMART acronym as
specific, measurable, attractive, realistic, and timeline (is clear). However, these goals were not as
detailed or comprehensive as requirements that I saw in industry projects.

During weeks 9-13, the team executed project tasks, while Margaret and I were monitoring and
controlling the project. We used a variety of assignments and check-ins with the students to make
sure they were on track with project tasks during this time. During this part of the semester, the

<table>
<thead>
<tr>
<th>Phase of Semester</th>
<th>Training</th>
<th>Initiating</th>
<th>Planning</th>
<th>Executing</th>
<th>Closing</th>
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</thead>
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<tr>
<td>Week</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3 4 5 6 7 8</td>
<td>9 10 11 12 13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Spring Break</td>
<td></td>
</tr>
</tbody>
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Figure 4.3: Semester timeline.
team and the PMs had to exercise time-management in order to overcome procrastination and stay on schedule. The team, Margaret, and I struggled to avoid delaying the deliverables during the last third of the semester because of many competing priorities in PEC and other courses. However, from my experience in industry, the last month before a delivery can be hectic as well. We managed to survive the push to the finish and completed all of the deliverables.

The team, Margaret, and I spent the last week and half of the semester closing out the project, presenting to stakeholders, and transitioning the deliverables to Adam. We also spent part of the last week reflecting on what we had learned throughout the semester.

The semester was very busy for Margaret and me. We both had a full course load including APM. Being a PM was a lot of work and I felt like the amount of work was not clear during the application and interview process. As PMs, we had the following PM responsibilities with the average number of hours per week in parenthesis:

- Attending APM class (2);
- Facilitating LTP class (3);
- Holding office hours (1);
- Grading assignments from our team (2);
- Completing our own APM assignments (2);
- Supporting the team and reviewing team deliverables (2);
- Maintaining organization and communications (1); and
- Creating lesson plans for each LTP class (3).

This totaled about 16 hours dedicated to PEC each week. The APM course was worth four graduate credits and therefore should have taken approximately 12 hours of academic work per week including class time. Three hours of academic work per credit is a common goal for most faculty and captured as a general rule in some handbooks, like the Committee on Courses of Instruction Handbook from the University of California, Berkeley (Academic Senate, 2015).

About every other week, I felt overwhelmed with the amount of work I had to do in APM and my other courses. Fortunately, the PEC staff was understanding and was flexible on the due dates of most of the PM assignments. Margaret and I continually negotiated about how to divide the
PM work between us. We were able to divide the work effectively between us. Sometimes when I was busy with other courses, Margaret took some extra work like grading. Then I returned the favor while she was busy with her other courses. Overall, I think we worked effectively as co-PMs. Although I had also felt overwhelmed as a project manager in industry, I found it easier to prioritize and manage my time in industry because I was also able to go to my manager or mentor to ask for help on how to prioritize my time or say no. However, as a PM in PEC I did not feel like I could go to my other professors and ask for extensions on assignments, and my exams were pre-scheduled. Exams were a common point of workload negotiations between us.

4.5.2.1 Specific examples of in-class activities

In this section, I will describe specific in-class activities that highlight interpersonal skills and knowledge areas of the PMBOK (2013). I was able to practice these interpersonal skills (listed in Table 4.5) and knowledge areas (listed in Tables 4.3 and 4.4) through each of the following activities. The first section covers develop project team process of the project human resource management knowledge area and the team building interpersonal skill. The second section highlights the collect requirements process of the project scope management knowledge area and manage stakeholder engagement process of the project stakeholder management knowledge area as well as the influencing and decision making interpersonal skills. The last section also illustrates the manage stakeholder engagement process of the project stakeholder management knowledge area as well as the communication and political and cultural awareness interpersonal skills.

4.5.2.1.1 Team building activities. In the first class session of my LTP section, the students, Margaret, and I introduced ourselves with names and majors; the introductions helped us to learn each other’s names and highlighted the diversity of the team. On Thursday of week two, we had our first client meeting. The team moved the desks into a circle to simulate a conference room table. To fill the time before our client arrived, Margaret and I reminded the students of the individual assignment due the following Monday and checked that the students had read the handout on active listening. When our client, Adam, arrived we passed out printed agendas to everyone. The agenda items included introductions, descriptions of the park and its staff, and suggest some possible directions for our project. Adam was a white male in his late thirties with brown hair and an average build. He was also an alumnus of the university, so he understood the campus. We were
the eighth PEC team that he had worked with, so he also understood the structure of the LTP course. We spent the rest of the time asking and answering questions about potential projects.

On the Sunday after the third week of class, we took a field trip to the park. We met in a parking lot on campus at 9:00 am then car pooled to the park, about a 45 minute drive. Mike, Luke, and Brian rode in my car. Emma, Isabella and Carrie rode in Margaret’s SUV; they picked up Noah on the way because he was running late. Carrie was enrolled in LTP at the time of the trip, but dropped the class a few days later. Brandon and Drew each drove separately because he had to leave early due to a conflict. Drew drove separately and met up with us at the park because he over slept. Ray did not participate in the trip because he had not attended class yet, even though he was registered for the course. Once we arrived at the park, Adam gave us a tour of the property, highlighting areas where we might be able to help with semester projects, the history of the property and the previous owner, and the results of previous PEC projects. Most of what Adam showed us was within 200 yards of where we had initially parked, however we drove in three cars, to two other remote areas of the park as well. In between those two stops, he drove us to one of the statues that is an icon of the park. It was surprisingly warm, about 50 degrees Fahrenheit, for a Sunday in early February in the Midwest. Some areas around the park were muddy from the melting snow, I was glad I wore hiking boots. All of these activities increased our understanding of each other and our client. We did additional in-class activities to gain a broader understanding of needs of our client and other stakeholders for our project.

4.5.2.1.2 Identifying stakeholder needs and solutions. During the third class, we did an in-class activity called “problem-solution trees,” which is a specific type of brainstorming activity. The goal of this activity was to identify problems and solutions in core areas of importance to the park. First, we divided the team into groups of three and gave each group two Sharpie markers and a large 25”x30” piece of white sticky paper to hang on the wall. We gave each group a core problem that Adam identified in the meeting at the student center. Each group of students wrote their problem in the trunk of their tree. Then each group listed possible causes of the problem as the roots of the tree. We encouraged them to record all of their ideas that came up and not to filter. After a few minutes when it seemed like ideas were not flowing as quickly, we prompted each team to pick one or two of the causes and think deeper about the root cause. For example, one tree identified problems with water use at our client’s park; see Figure 4.4. The final step of the activity was to capture possible solutions as the leaves of the trees. We encouraged each group to
find at least one leaf for every root that they had identified. Once each group had attached several roots and leaves onto their trees, we rotated the groups. Each group spent an additional two to five minutes looking at and adding to each of the other two trees before the end of the activity. This activity achieved the goal of identifying the root causes of the problems and new solutions we had not yet considered. Once we identified potential solutions we could undertake, we also had to explore the political or cultural impacts of our solutions.

Figure 4.4: Photo of a problem-solution tree created in our LTP class.

4.5.2.1.3 Building political and cultural awareness. In week nine, we did a role-playing game in class. The goal of our game was to get students to think about our project and deliverables from the perspectives of a variety of different stakeholders. Before class, we wrote names of 13 different stakeholders on 3x5 index cards and put example scenarios in our lesson plan for the day. Unfortunately, other activities planned for that day took longer than expected, so we were not
able to complete all of the role-playing scenarios. Before we started the game, the team, Margaret, and I, rearranged the desks in the room to form a circle. I removed index cards for stakeholders not needed in the first scenario. To assign the roles randomly, each of us (including Margaret and I) drew an index card from the stack of stakeholders. Then, I explained the scenario to the students; it was a pitch about a proposal that we were preparing Adam and maintenance team. One team member played the role of the student making the pitch (but not a team member directly involved in creating the proposal), another student played the head of the maintenance team, a third student played the role of Adam, and I played the role of the park’s executive director. We rotated the key roles with each scenario and continued the game until the class was over. This role-playing game was successful in that the team started thinking about some of the deliverables from the perspective of the other stakeholders. For example, subsequent in class discussions the team had deeper discussions about tradeoffs between efficiency, budget, and aesthetics that had not been emphasized before the role-playing game. They also started discussing the need for testing and understanding the logistics of implementation that had not been considered prior to the role-playing game even though Adam briefly mentioned these logistics during our in-class meeting and park tour. We had hoped to revisit the role-playing game again in the semester, but there was not enough time.

4.5.2.2 Analysis and reflection

The LTP course seemed to start slowly. Margaret and I were still learning a lot about our roles, and there was a lot of introductory material to cover with the team in class. If I were to reorganize the LTP course, I might try to speed up the planning phase so that more time could be spent in the execution phase. Some feedback from the LTP students indicated they also felt that the beginning of the course dragged out a bit as well.

During the semester, we covered the entire life-cycle of a project and, therefore, all of the process groups in the PMBOK (2013). I think that experiencing all phases of the project was critical to the comprehensive learning experience of PEC PMs, because some skills and knowledge areas listed in the PMBOK (2013) are specific to the phase of the project. For example, most of the project scope management knowledge area is concentrated during the planning phase of a project. During the planning phase it is important to have clear documentation of decisions made and the rationale for the decision. Otherwise, team members joining later in the project may skip a key step or
work on a deliverable that is not necessary. In our LTP section, all of the students were actively participating the course related activities by the time the Project Charter was submitted, so they should have understood the content and rationale for each deliverable. However, my experience in industry was that teams were much more dynamic and team members and even project managers changed during the course of a project, so documentation was much more important in industry. While I was in industry, I did not experience the entire life-cycle on any one project, but I did have a chance to work on all phases at some point. Therefore, I think it was important to experience all phases of a project in PEC.

4.5.3 Tracking progress and motivating the team

Margaret and I provided biweekly status reports to the PEC staff. The status reports included a high-level summary, completed and upcoming project tasks, risks, highlights for the next two-week period, funding updates, grading status, and any other notes for the staff. The dates and status were highlighted with traffic light colors to make it easy to the status with a quick glance. These status reports were very similar to what I submitted in industry.

Throughout the semester, we did status updates of project deliverables, in the LTP course. The master task list (MTL) is a spreadsheet tool that the PEC staff provided for LTP teams to keep track of project tasks and sub tasks. The MTL was in a Google Sheet that all students, PMs, and the PEC staff had access to throughout the semester. We asked the LTP team to keep the MTL up to date and approximately once a week, we displayed the MTL with a projector on a screen in class to remind everyone of where we were in the project and where we were supposed to be. By marking subtasks complete in the MTL we were able to celebrate successful progress on deliverables. It also highlighted to Margaret and me which students we needed to follow up with to determine why they were falling behind schedule. Noah noted that he appreciated the social pressure the MTL provided to the team.

On the Thursday of Week 6, Margaret and I led an activity in class on values based on an activity from The Student Leadership Challenge (Kouzes & Posner, 2008). On the top of the worksheet, there was a list of about 35 personal and professional values organized into four columns with four blank lines at the bottom of the fourth column. Some of the values on the list were autonomy, creativity, health, quality, success, winning. First, each student circled 8-10 values from the list. Then, each student narrowed that list to their top five and finished the sentence “This value is
important to me because...” Then we transitioned to organizational and team behaviors. The students reviewed a checklist of behaviors of dysfunctional and functional teams based on the Patrick Lencioni (2002) book, *Five Dysfunctions of a Team*. After both of these activities, we had the team create a team contract that captured our shared values. Margaret wrote the ideas on a 25” x 30” white sticky note affixed to the chalkboard while I facilitated the discussion of what to add to the list. Some items on the team contract included “accept constructive feedback,” “ask for help,” “accountability,” being prompt, and “do your work for quality and results.” Some of the more surprising items were “no cop-outs” and “boldly go where no PEC class has gone.” By adding “no cop-outs” to the contract, the students wanted to note that no one should avoid doing their part of the project. Once everyone agreed we had captured everything, we asked each of the team members sign the contract; then, Margaret and I also signed the contract. We brought the contract back to class in Week 7 and asked the students who were absent during the team contract activity to read and sign the contract. Later in the semester when the team was not meeting deadlines, we brought the contract back to class to remind the team of our agreement.

Toward the end of the semester, Margaret and I realized that tracking task progress with the MTL was not working effectively. The MTL included 94 rows of subtasks and seemed like it might be hard for some students to navigate. Not all of the students were updating their status in the MTL and most of the deliverables were behind schedule. We decided that a visual aid that showed the status of each deliverable at a quick glance might convey the status of each deliverable more clearly to the team. We wanted the new visual aids to be easy to maintain and in a form that would be easy to bring to class each day. So, Margaret created a ladder on a large sticky note to show progress on each infographic deliverable; see Figure 4.5. The intent was to mimic thermometer like posters that illustrate progress in a fundraiser; however, instead of dollar amounts at each increment, we used project tasks. Then in class on Thursday of week 10, we had the team break into smaller groups and create similar ladders for the rest of the deliverables. Each deliverable had a small, brightly colored sticky note with the name of the deliverable. The location of the deliverable sticky note marked the progress on the ladder. We brought the ladders to class each day so that each student could update their progress.

On Thursday of week 10, Margaret and I also facilitated a stop/start/change/continue activity in class. First, students wrote activities or behaviors that the team should stop doing, start doing, change what they were doing, or continue doing. They each had two different color sticky notes, teal
for the team and purple for leadership (the PMs, PEC staff, or client). Then, to keep the feedback anonymous, they each put their sticky notes on the chalkboard in each of the four categories. We were, unfortunately, running low on sticky notes that day so some students tore their notes in half so they could contribute more ideas. Once all the notes were on the board, Margaret and I grouped similarly themed ideas. Finally, as a team, we agreed on actions for the rest of the semester.

After major assignments in the course, we brought treats for the class. After we delivered the Project Charter to the client, we brought a box of Dunkin’ Donut Munchkins (donut holes) to class. Several team members thanked us for the donuts. We also brought a box of donuts from Dunkin’ Donuts to class at the end of the semester after we transferred all of the deliverables to the client.
4.5.3.1 Analysis and reflection

As a project manager in industry, I was primarily responsible for tracking the schedule and budget of the project I was working on. I thought the PEC experience closely resembled my industry experience. Finding an effective way to track project status was key in both places. Margaret and I had to experiment with a few ways to track status that the LTP team also felt comfortable using as well. The bi-weekly status reports in the PEC program closely resembled the status reports I submitted monthly in my industry position. While tracking status was similar, there were also two major differences between PEC and industry: task planning and motivation. I did not have any benchmarks or data to know what was realistic for nine undergraduates to complete in about seven weeks. In contrast, in industry we had benchmarks and data that accurately estimated task duration.

In industry, I was fortunate to work with several diligent teammates and I did not have to do as much to keep them motivated. Sometimes there were team members had conflicting priorities, but that was easily resolved by talking to the department leadership. Treats, like donuts, did motivate my teams in industry as well. Motivating the LTP team was a bit more difficult. Some LTP team members were more motivated than others were. Emma and Luke were always on top of their parts of the project and team assignments while Ray and Brian did not contribute unless we specifically asked.

Tracking progress and motivation covered many areas of the PMBOK (2013). We used skills in the project integration, time, and risk management knowledge areas. We also practiced the following interpersonal skills: leadership, team building, motivation, and coaching. In addition, tracking progress covered monitoring and controlling which is the only process group not mentioned in the timeline (Figure 4.3).

4.5.4 Giving and receiving feedback

Throughout the semester, there were multiple opportunities for all of the PMs to receive feedback on our jobs and for the PMs to provide feedback to their team. Some forms of feedback were more formal than others. At the middle and end of the semester, all PMs specifically asked their team to fill out feedback forms about how we were doing. Margaret and I were also able to infer how well we were communicating expectations to the students while grading. We provided formal feedback to the team through grades. The team also completed peer evaluations of each other twice during
the semester.

4.5.4.1 Project manager feedback

After Margaret and I had graded the first two assignments (one individual assignment and one team assignment), we realized that the team did not understand the expectations of the assignments. For both of these assignments, we handed out the assignment instructions in class and gave the students about three minutes to read the handout. Each assignment had at least two pages of instructions and were assigned on different days. After the students had read most of the handout, Margaret and I highlighted a few key points. Then we asked a general questions like “are there any questions?” or “do you understand the assignment?” In subsequent classes we reminded students of the due dates of both assignments by writing reminders on the chalkboard and announcing the due dates before the end of class. Several weeks we also sent announcement emails to the team. We always used in-class announcements and rarely sent announcement emails because we wanted to encourage the team to attend class.

After we graded the first two assignments, we revisited both in class. For the individual assignment, we spent an additional 5-10 minutes in class going over the description of the assignment, then had each student review their own assignment. We printed out copies of their ungraded individual assignments and returned them with a blank assessment rubric. The assessment rubric highlighted what we were looking for when we graded. We gave them the rest of class (approximately 5-10 more minutes) to review their own work based on the assessment rubric and ask us questions. Before the students left we provided a new due date for them to revise and resubmit the assignment and suggested that ask us questions if they were still confused about what was expected.

For the team assignment, the biggest deficiency was that they did not proofread the complete document. So, we created an in-class activity on proofreading. We split the team into smaller groups of two or three. Then we provided each subgroup a box of different color pens and highlighters as well as two pages of the team document. The blue highlighter was assigned to statements not backed by evidence, the yellow highlighter to statements that lacked proper citations, the orange highlighter to statements that were biased or unprofessional in tone, the pink highlighter to statements of fluff, and the green highlighter to statements that were incorrect. The black pen was used to circle grammatical or spelling errors, the blue pen was used to circle uses of first person,
and the green pen was to identify any other comments the students identified. We marked the first page as an example. Mike was not in class the day we completed this activity, however another student showed him the marked up document in a team meeting outside of class. The next class he pointed out that when he read the marked up document, it was hard for him to determine the category of problem because he is colorblind. Even though he was not able to distinguish the colors, he was able to understand the mistakes by looking at the description of each category on the handout. Therefore, he understood the types of mistakes that Margaret and I were looking for while grading assignments. Overall, the proofreading activity was successful: on all subsequent assignments, the students improved in these areas. Once we realized there were misunderstandings we also made a conscious effort to ask better questions to gauge comprehension. For example, for the third major assignment, we provided the handout in Tuesday’s class and asked them to read it before Thursday’s class. At the beginning of Thursday’s class, we asked them to list the four major components of the assignment on an index card. We did not always have formal checks like this, but we did try to move from questions like “does that make sense?” or “do you have any questions?” to more specific questions like “can someone describe what should be included in the deliverables section?”

On Thursday of week 7, Margaret and I asked the students to fill out anonymous feedback forms (one for each of us) on how we were doing as project managers. The form had ten questions that asked for a numerical rating. The leadership-related questions were as follows:

- the project manager is well-prepared for class;
- how would you characterize the ability of the project manager to explain;
- the project manager encouraged your participation in class; and
- the project manager is easily approachable.

The form also included open-ended questions including asking for our strengths and weaknesses as project managers. Margaret and I calculated numerical averages for our own ratings and summarized the comments before our APM class the next day. During our APM class, we each talked about the results in groups of two or three PMs of other sections. After analyzing this feedback and talking with other PMs, Margaret and I realized there were two major misconceptions among the team. First, at least two of the students misunderstood our roles as co-PMs: They saw us more as teaching assistants (TAs) rather than traditional project managers. We were both surprised that
on average the team rated Margaret as being less fair about grading than me. We were surprised because we collaborated on grading. Second, we realized that the students did not understand the purpose of some assignments and classroom activities. In the Thursday class of week 8, we planned a group discussion. Toward the end of class, Margaret and I asked the team to help us make a circle with the desks. We started by explaining the differences and similarities between PMs and the TAs in other courses on campus. One of the major differences we highlighted was that as PMs we were responsible for the quality of the project deliverables and maintaining a professional image to the community we were working in. Then we asked the students how we could better communicate the rationales for assignments and activities. One suggestion was that we spend more time in class going over the assignments.

We also looked for other unspoken and informal feedback. At the beginning of the semester, we said that we would be available via appointment for office hours. However, none of the team asked us to meet them during office hours even though it seemed as if some of them had questions. So, Margaret and I each picked two different hours each week for office hours. Once we had prescheduled time team members began coming to office hours for help on the project or assignments.

At the end of the semester, more than one student took the time to send us a thank you email. Luke said “Thank you again for a wonderful semester and for being such helpful PMs for myself and the entire team. We could not have created and finished so many quality deliverable items without your help.” Positive feedback like this from students was reassuring for me.

4.5.4.2 Student feedback

On Monday of week 6, each team member turned in anonymous midterm peer evaluations. On the team evaluations, they needed to give each team member (including themselves) a grade from 0-100 and write at least one positive statement and one possible area of improvement. Before we met with the students on Tuesday evening, Margaret averaged all of the grades and summarized the positive comments and feedback for each student. Then we met with each team member individually. In each meeting, we summarized the positive and negative feedback that other team members provided. We also talked with each student about what he or she could do to improve for the rest of the semester. During the performance review, we made sure they each had one actionable task for improvement. Emma received feedback from her peers that she was not attending enough of the evening team meetings. When we asked why she was not attending these meetings, she indicated
that she did not feel comfortable walking back to her car in the dark. So, we suggested that she ask a teammate to walk with her and provided the phone number for the Safe Walk service on campus. Both Emma and Isabella rated themselves significantly lower than most of their peers rated them. I understood why Emma and Isabella might have felt during the peer evaluation process; because I rated myself lower than my manager during a similar performance review in industry. We used the data from these reviews to adjust the grades for the team assignments.

Throughout the semester, the ongoing conflict with the team seemed to be freeloaders. Several students mentioned in the mid-semester evaluations that some teammates were not contributing equally to the project. We tried several techniques to encourage everyone to contribute to the project. We asked some students to stay after class to see if there was anything, we could help with on their part of the project. In the mid-semester peer evaluations, Ray received scores significantly lower than the rest of the team because he was not contributing to team documents or attending meetings (freeloading). We scheduled a longer midterm review with Ray to allow time to discuss the peer evaluations and other missing individual assignments. After spring break, Isabella, Brian, and Brandon seemed as if they were not contributing as much as other students. We asked each of them to stay after class on different days. If after conversations it still seemed as if a team member was freeloading, we adjusted their engagement and professionalism assessment (EPA) points accordingly. There were 25 EPA points assigned every three weeks throughout the semester. If we deducted EPA points, we provided feedback via Blackboard grade comments about why points were deducted and how he or she could improve during the next three weeks. Unfortunately, none of these techniques worked completely: Ray freeloaded the entire semester. His course grade also reflected his lack of effort.

Throughout week 13, Margaret or I met with each team member to review his or her deliverable and provide feedback. We used Doodle to facilitate scheduling of the one-on-one reviews. In each meeting, one of us met with the student and discussed the expectations for the deliverable based on the Project Charter and client expectations, reviewed the deliverable, and provided suggested and required changes before it could be delivered. Margaret and I kept a spreadsheet of each deliverable to track the status of reviews and changes.
4.5.4.3 Analysis and reflection

Grading student work and providing feedback is a form of evaluation, but it differed from the peer reviews of requirements and software (artifacts) I performed in industry. When I performed a peer review in industry there were clear checklists and standards to follow, I just documented what was wrong and sent the artifact back to the person who created it to fix and submit for re-review. During peer reviews, we placed emphasis on safety and quality. The industry checklists resembled the rubrics that I used when I graded student work in the PEC program. Unlike the peer reviews in industry, however, in PEC we emphasized learning; so my feedback needed to be more detailed and nuanced than the peer reviews in industry. In both situations, the person was able to fix problems based on feedback and resubmit the work. However, in industry it was required, and in PEC the student only resubmitted assignments if they wanted to try to improve their grade. The biggest difference between industry peer reviews and grading was turning mistakes into numerical grades.

4.5.5 A challenging incident

On Tuesday evening of week 6, Margaret and I were sitting in padded chairs in a corner of a common area of the undergraduate library. The team was in a nearby study room working on the Project Proposal, which was due the following Monday. Each team member took turns leaving the group to meet with us. We were providing each team member with a summary of feedback from the mid-semester peer reviews. After we had completed all of the feedback meetings, we decided to stay in the library and work on our own homework; by remaining in the library, we would be available to answer questions from the team.

Before I started my homework, I checked my email. I was particularly perplexed by one email message in my inbox. The email message originated from the university’s online directory for student organizations, so the sent-from address was generic. The email message was signed “Thank you!” and no name. However, two other phrases in the email caught my attention: “research for a class” and “go on retreats.” I showed the email message to Margaret and asked, “Are they over there sending emails to presidents of student organizations?” She looked at the email message and was also confused. Our confusion stemmed from our understanding of the project status and the apparent misunderstanding of the status by the team. One general area Adam mentioned we could work during the semester was advertising and drawing more students to the park. One idea that we generated was to determine the types of events that student organizations hold and if
the facilities at the park would support those activities. However, both Adam and the PEC staff warned Margaret and me that we needed to have a specific plan approved by all stakeholders before proceeding with idea. Margaret and I thought we had relayed this warning to the team. However, since the team was moving ahead with the market research there was clearly a misunderstanding.

I turned to Margaret and said, “I should probably go over there, and figure out what is going on.” She agreed. She stayed with our belongings in the common area, and I walked over to the study room that the students were using. When I opened the door about six team members were sitting around the table and a couple of them had laptops in front of them. I started by asking, “Are you sending emails to student organization presidents?” Every student in the room turned to look accusingly at Isabella. Then Mike chimed in and said, “Did you send that to her?” After that question, there was a bunch of nervous laughter in the room. It felt like everyone was uncomfortable with the situation, including me, and that it would be easy for all of us to become defensive. So, I decided to keep my follow up short and to the point. I wanted to stop them from sending more emails and convey a couple key problems with what had happened. First, they did not provide any contact information for answers to the questions in the email and it was unprofessional because there were grammatical errors in the email. Second, we needed to wait and determine how to proceed with this task as we finished the project proposal and received feedback from Adam and the PEC staff. Then I left the room and went back to sit with Margaret.

The next class period had planned activities that would fill the entire duration. We started by having the team fill out feedback forms for Margaret and I. Then we moved on to the activities for the day. Fortunately, we had already planned topics on values, team dynamics, and ethics. All of these topics allowed us to talk about how we were going move forward on the project without explicitly pointing to the emails sent by Isabella earlier in the week. In this class period, we also created the team contract mentioned earlier.

After Margaret and I reviewed the feedback provided by the team, we realized there might still be some confusion on our role and why sending the emails was a bad idea. The meeting to discuss details from the feedback forms mentioned earlier, happened a week after this incident (Thursday of week 7). From the conversation and nodding heads, it seemed like the students that participated in the conversation better understood our role as PMs. However, Mike was not in class on Thursday of week 7. He had emailed Margaret and I and stated that he was confused about why I was so mad about the emails because he thought it was a good idea. From his email message it was clear
that the root of his misunderstanding over this incident was our role as PMs. I replied to the email to help clarify the misunderstanding. I explained to Mike in more detail about the role of the PMs in controlling quality and meeting stakeholder expectations. I also explained the planning process at the beginning of the semester was a necessary step to ensure our deliverables were well planned and received stakeholder approval before moving forward.

4.5.5.1 Analysis and reflection

I am not sure how this incident would have played out if Isabella did not send the email message to me. In hindsight, two misconceptions led to this misstep: confusion in our role as PMs and not TAs, and misunderstanding of the purpose of the Project Charter as a binding agreement with the client and PEC staff. If I were to be a PM in this situation again, I would definitely emphasize two differences between PEC and other class projects at the beginning of the semester. First, my role as a PM is a combination of a project manager and TA. Second, since there is a real client the deliverables need to meet his needs and be approved before proceeding with development.

This incident is the reason why working with a team of real people adds to the authenticity of the experience. During this incident and in similar situations when my team made mistakes in industry, I was in the position to be the first one to defuse the situation and look for a solution. Therefore, it was a very realistic experience from my perspective. It was a great chance to practice conflict management and coaching skills. Both are listed as interpersonal skills in the PMBOK (2013).

4.6 Comparison to other experiences

To gain further perspective on my PEC experience, I compared it to my time as a project manager in the aerospace industry to determine if PEC PMs were learning skills that would prepare them for future roles in industry. I also interviewed four other PEC PMs about their experiences in the APM course and as a PM. After the interviews, I was able to determine that the experiences of PEC PMs is similar but the program has implemented improvements during the past two years.
4.6.1 Similarities and differences of PEC and industry

During my time as a PEC PM, I had several experiences that were similar to my experience as a project manager in the aerospace industry. However, there were also times when my PEC PM experience was quite different from my experience in industry.

4.6.1.1 Similarities

Three activities were about the same as a PEC PM and as a project manager in industry. These similarities included tracking the status of tasks, communicating with stakeholders, and the final push to complete tasks for an on time delivery.

4.6.1.1.1 Tracking the status. One of my primary functions in industry and as a PEC PM was tracking the status of tasks on the project. Tracking the status included reminding the person assigned of an impending due date or sometimes that their task was overdue. If a due date was close or past due, I would also offer my support to help finish the task. As another part of tracking status, I ensured that dependencies were documented and communicated between the responsible parties. A dependency between tasks means that the first task needs to be completed before the next task can start. Frequently, the person responsible for the first task is not the same as the person responsible for the subsequent task, so communication between the responsible parties is key. While dependencies exist in most projects, I found that people I worked with in industry understood dependencies better than my LTP team. I think the dependencies were better understood in the aerospace industry because most features followed a similar path: requirements, design, code, and test. In addition, we documented each feature using Gantt charts with visual links to illustrate dependencies. I paid close attention to dependencies because, for most features, all steps needed to be complete before a delivery so an early missed due date could mean that the feature is not completed on time. Since my team in industry understood the dependencies, they took care of some of the communication on their own. For example, the person working on design would tell the person working on code when it was ready for coding to begin. Unfortunately, since my LTP did not fully understand the dependences, that communication fell back to Margaret and I. Whether I used Gantt charts, spreadsheets, or the ladders of progress (see Figure 4.5) mentioned earlier, I found that there was not a easy and organized way to keep the tasks status up to date. In both PEC and industry, I experimented with many different tools for tracking status and communicating
due dates with my teams.

4.6.1.1.2 Communication with stakeholders. Another function as a PM is to communicate with stakeholders. While this task is just as important as tracking status, I found that it usually took less time. In both industry and PEC, I communicated directly with the primary stakeholders: the client and my leadership. When communicating with the client, my goal was to build trust and make sure the product we were developing met their needs. In PEC, my leadership was Wendy and Sam. Margaret and I sent bi-weekly status reports to them that included the status of project deliverables, risks, and the status of other PEC PM tasks like grading. In industry, my leadership included leaders within my department and leaders for the entire project (which usually included multiple departments). The status reports that I sent in industry had similar information, they just varied in frequency, detail, and format depending on the audience. The other similarity was that I used a traffic light color code on all of the status reports that I submitted.

4.6.1.1.3 Final push to finish before delivery. In PEC and industry, I found that no matter how much I planned and tried to keep the project on schedule, there was always a big rush to finish everything before a delivery. It seems like the tasks right before the delivery always had less time available to complete than was planned for them to take. For example, in PEC this meant we did not have as much time to get outside feedback on our infographics as we planned. In industry, it usually meant working a different shift in order to get testing done. I also found that the push to get a delivery done was stressful for the entire team. In both PEC and industry, I pitched in, helped the team manage stress, and together we finished the project on time.

4.6.1.2 Differences

I also identified four major differences between PEC and my industry experience. These differences included team building activities; defining task scope and duration; confusion in roles; and the amount of proofreading required.

4.6.1.2.1 Team building activities. In PEC, we did several formal team building activities, like the start/stop/change/continue activity described in the previous section. However, in industry we only introduced ourselves in a team meeting and sometimes had a party after a major delivery. Perhaps the difference was because in industry we already knew each other from other projects or
because we did not meet as often as a team. In PEC we met as a team in class every week for 160 minutes (two 80-minute class sessions), whereas in industry we met as a team for 60 minutes or less each week. In PEC, class time was devoted to learning about being on a team, about the customer, and about completing projects. So, there was time and value added in completing team building activities. Whereas in the 60 minutes we met each week in industry, we focused on task status and problems preventing tasks from moving forward. After comparing both experiences, I wish I would have created a team contract with my team in industry. The team contract we created in PEC was helpful in holding everyone accountable, especially during stressful times of the semester.

4.6.1.2.2 Defining task scope and duration. One of my biggest challenges in PEC was determining the scope and duration of the tasks for our project. I had no idea what was reasonable for a team of nine undergraduates to complete during the semester. We wanted to have enough deliverables that it would require each team member to contribute to the project at the level expected for the course but not too many deliverables that there was too much work for the team to be successful. Once we had our draft list of deliverables, Margaret and I took the list to Wendy and Sam for feedback. They said our list looked about right; unfortunately, they did not explain their rationale for arriving at that decision. They also did not have information to help us determine how long to expect a student would take to complete each deliverable. This ambiguity in scope and duration was completely different from my experience in industry. Based on historical data we had estimates down to the hour how long a task should take an average engineer. The task estimates made planning schedules and scope much easier in industry.

4.6.1.2.3 Confusion in roles. In industry, my role as a project manager was clearly defined. I was responsible for leading my team to deliver a safe, high quality software application that met the needs of our client. My team understood the processes and procedures they needed to follow as well as the chain of command for decisions and deviations from the project plan. In PEC, my role was not as clear to me or the students. My confusion was due to the co-PM role. I felt like I needed to discuss everything with Margaret prior to doing it. Margaret and I did not have a clear separation for most of what we did so we asked for the other person’s approval before proceeding. By trying to keep everything shared, we probably created more confusion and work for ourselves. The team also confused our roles as PMs and instructors. There was at least one LTP team member that did not understand that we had more responsibilities as PEC PMs than an instructor or TA in a
traditional course. As PEC PMs we were also responsible for teaching related activities like leading in-class activities and grading. However, as PEC PMs we were also responsible for delivering a high quality project that met the needs of our client.

4.6.1.2.4 Proofreading documents. Another difference in PEC was that I had to spend more time proofreading documents than I did in industry. In industry, our leadership set an expectation that we proofread our own documents for spelling, grammar, and format before submitting them for peer review. Therefore, most of the documents I read from my team in industry were mostly free of spelling and grammar errors. The same was not true for the documents submitted by the LTP team. Perhaps, Margaret and I did not set clear expectations for the LTP team. After the in-class proofreading activity described in the previous section, the documents the LTP team submitted were better. However, Margaret and I still had to correct several grammar and spelling errors before the document was ready to submit to our client.

4.6.2 Perspectives from other PEC PMs

I interviewed four other PEC PMs to gain insight from other insights about the PEC experience from different perspectives; see Table 4.1. During each interview, I asked each PM to indicate which of the skills in the PMBOK (2013) they had learned as a PM in the APM course. In the first column, they placed a checkmark if they used the skill as a PM, in the second column they placed a checkmark if they learned about the skill in the APM course, and in the third column, they placed a checkmark if they did not learn the skill or remember covering the skill in the course. The first two columns were not mutually exclusive: we learned about most skills in the APM course and developed the same skills as project managers. Since some of the terms in the PMBOK were not the same terminology we used in APM, I also provided a brief definition of each skill on the form. I also completed the form based on my experience in APM. Exhibit 8-Exhibit 10 show the total number of responses to each item for the project management knowledge areas, interpersonal skills, and process groups respectively.

4.6.2.1 Analysis and reflection

Based on the process groups, interpersonal skills and knowledge areas from the PMBOK (2013), the experiences of the other four PMs were similar to my experience as a PM. Each PM participant
experienced or learned about each of the process groups; see Exhibit 10. The three PMs from the 2014-15 academic year (James, Margaret, and I) each learned or experienced all of the interpersonal skills. However, Panther and Lily indicated that some of the skills were not covered by their experience. During the interviews with Panther and Lily, it became clear that the PEC staff had made improvements to the APM course between the fall semester of 2013 and the fall semester 2014. The changes in the course might explain the difference in experience.

We each had slightly different experiences related to the project management knowledge areas as well. For example, James and I indicated that we did not cover the perform integrated change control process. Our difference in interpretation could be due to our industry experience. In my experience, a baseline must be established prior to tracking and integrating changes. Therefore, since we only had one delivery to our client, there was not a baseline to make changes to, thus I did not use an integrated change control process. Additionally, Lily and James indicated that they did not cover most of the project risk management knowledge area while the other PMs indicated they did have that experience. The difference in risk management experience could be because each PM worked with a different client and had different project deliverables. Because we worked on different projects, we also had different experiences in the project procurement knowledge area.

4.6.3 Limitations

This study has three major limitations, including the location, the organization of PEC, and the data collected. PEC is a program at a large, public university in the Midwest. The large and diverse student body allowed for diverse groups of students in both the APM and LTP courses. The students in PEC had a variety of majors from across campus. Both international students and domestic students enrolled in both courses as well. Unfortunately, the PMs interviewed in this study were all domestic students. A smaller more specialized school may not have as diverse of a student population to draw from.

Second, the use of TAs in classrooms is widely accepted. The prevalence of TAs in undergraduate education could have contributed to the confusion of roles for the PMs. Since the precedent for TAs in the classroom had already been set, it might have been easier to set up PEC so that the PMs were leading the LTP course each day. The university training for TAs and the pre-semester training for PEC PMs were very similar. The PEC staff attended two class sessions of each LTP section during the semester. The organization of PEC allowed each LTP team to work with a real
client, so there was not a way to study a two-course project experience without real clients.

Finally, there were limitations to the data I collected. My field notes were not as detailed as they could have been. It was hard for me to take detailed field notes while I was leading the LTP classes. Perhaps it would have been helpful to video or audio record key classes during the semester. However, video recording may have been intrusive in the classroom. Due to a professional conflict, I missed one day of the LTP course and two days of the APM course. In addition, the team assignments were protected by Family Educational Rights and Privacy Act (FERPA) and therefore not included in this study. Having access to these assignments may have provided more insight into the reactions of the team and understanding their perspective.

4.7 Implications for practice

This study provides an example of experiential learning for project management. From this study, several recommendations are provided for other courses and project management training. The recommendations are based on my experience and recommendations from the other PMs that we interviewed.

4.7.1 Designing college courses

Reflection was a key component in PEC assignments. Both Kolb (2014) and Schön (1983) emphasize the importance of reflection in the learning process. We had many opportunities for feedback and experimenting with PM skills that we learned in class. The feedback and experimentation were both inputs and results of reflection activities. The PEC staff also supported the PMs throughout the semester and provided additional feedback and insight on our reflection assignments and during our group discussions in APM.

Two PEC organizational components led to a comprehensive project management experience: serving as the PM for the entire semester and working with real team members and stakeholders. PEC included all phases of the project life-cycle, and by serving as the PM for the entire semester, I was able to practice all of the skills and processes associated with each phase. When I participated in other projects courses, I was not able to serve in the leadership role for the entire semester, changing limited my experience as a leader. Additionally, as PEC PMs, we worked with real stakeholders and team members. Working with others on the project, instead of a simulation,
allowed me to practice the interpersonal skills listed in the PMBOK (PMI, 2013). I feel both of these components were key to the PEC experience and should be considered in the development of other project management courses.

As PEC PMs, we were not financially compensated, but we received four graduate-level course credits upon successful completion of the APM requirements. However, we all agreed that workload we had as PMs was not equivalent to the workload in other four-credit graduate courses. Lily and Panther suggested that more support for the course timeline and lesson planning would be helpful in reducing their workload. By the time James, Margaret, and I were PMs, more resources for the semester timeline and lesson plans were provided in the APM course. PM workload should be considered when developing project management courses like APM.

4.7.2 Training industry professionals

During APM, we each completed three reflective journal assignments. In each journal we described an experience, then we examined the experience through research and reflection, after that we described what we learned. After completing these journals in APM, I feel that formal reflection would have been helpful during industry leadership training and experience as well. Schön (1983) describes many potential benefits of reflection as a practitioner in a variety of industries. Several training courses I attended included group discussions but formalized individual reflection was much less common. Timely positive and constructive feedback is also important for industry professionals.

4.8 Conclusions and future work

During my experience as a PEC PM, I demonstrated all of the process groups, most knowledge areas, and all of the interpersonal skills described in the PMBOK (PMI, 2013). Some tasks, like grading, do not seem to be related to project management at first blush; however, I found that grading was analogous to reviewing documents and requirements in industry. Overall, I feel that the PEC PM experience represents most of the project management model and is a beneficial form of experiential learning for the PMs. I learned more about being a PM in PEC than I did in the project management course I took with a simulated project and team. Additionally, since I was the project manager for the entire semester, I was able to experience all phases of the life-cycle as
a PM, unlike courses where the role rotated throughout the term.

With some slight modifications to APM, students would be ready to apply to become a Certified Associate in Project Management (PMI, 2015a). The PEC PM experience has several similarities to project management responsibilities in industry. Each PM gains a set of transferable skills that will prepare them for project management roles in industry. Obtaining one of these certifications would provide a credential recognized by industry and documentation of the skills learned as a PEC PM.

My future work includes a more detailed analysis of the data collected during my experience and from other PEC PMs. The additional analysis would include other theoretical frameworks to uncover hidden beliefs or cultural norms of project management. Since most theories of project management are about roles in industry, the additional analysis will also reveal additional similarities and differences between the PEC program and similar roles in industry.
Table 4.3: Exposure to first five of the project management knowledge areas.

<table>
<thead>
<tr>
<th>Knowledge Area</th>
<th>Experienced as a PM</th>
<th>Learned in APM</th>
<th>Not Covered</th>
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</thead>
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<tr>
<td><strong>Project Integration Management</strong></td>
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<td></td>
</tr>
<tr>
<td>Develop project charter</td>
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<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Develop project management plan</td>
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</tr>
<tr>
<td>Direct and manage project work</td>
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<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Monitor and control project work</td>
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<td>0</td>
</tr>
<tr>
<td>Perform integrated change control</td>
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<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Close project or phase</td>
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<td>5</td>
<td>0</td>
</tr>
<tr>
<td><strong>Project Scope Management</strong></td>
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</tr>
<tr>
<td>Collect requirements</td>
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<td>Define scope</td>
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<td>Define activities</td>
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<td>Control schedule</td>
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<td>Control quality</td>
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Table 4.4: Exposure to last five of the project management knowledge areas.

<table>
<thead>
<tr>
<th>Knowledge Area</th>
<th>Experienced as a PM</th>
<th>Learned in APM</th>
<th>Not Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Human Resource Management</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan human resource management</td>
<td>5</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Acquire project team</td>
<td>3</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Develop project team</td>
<td>5</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Manage project team</td>
<td>5</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td><strong>Project Communications Management</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan communications management</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Manage communications</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Control communications</td>
<td>5</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td><strong>Project Risk Management</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan risk management</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Identify risks</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Perform qualitative risk analysis</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Perform quantitative risk analysis</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Plan risk responses</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Control risks</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Project Procurement Management</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan procurements</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Conduct procurements</td>
<td>1</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Control procurements</td>
<td>1</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Close procurements</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td><strong>Project Stakeholder Management</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identify stakeholders</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Plan stakeholder management</td>
<td>5</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Manage stakeholder engagement</td>
<td>5</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Control stakeholder engagement</td>
<td>5</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 4.5: Exposure to interpersonal skills.

<table>
<thead>
<tr>
<th>Interpersonal Skill</th>
<th>Experienced as a PM</th>
<th>Learned in APM</th>
<th>Not Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leadership</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Team building</td>
<td>5</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Motivation</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Communication</td>
<td>5</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Influencing</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Decision making</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Political and cultural awareness</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Negotiation</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Trust building</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Conflict management</td>
<td>4</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Coaching</td>
<td>5</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.6: Exposure to process groups.

<table>
<thead>
<tr>
<th>Process Group</th>
<th>Experienced as a PM</th>
<th>Learned in APM</th>
<th>Not Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiating</td>
<td>4</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Planning</td>
<td>5</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Executing</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Monitoring and controlling</td>
<td>4</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Closing</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>
As presented in Chapters 2, 3, and 4, I conducted three studies related to experiential learning. In Chapter 2, I compared traditional on-campus laboratory equipment with a new affordable and portable laboratory kit. Based on the data collected, the experiences of students using each type of equipment were similar. In Chapter 3, I surveyed control systems faculty and industry practitioners in order to determine common aspects of undergraduate control systems laboratories. In this study, I identified eight most important laboratory objectives, thirteen most important concepts, and nine most important components of laboratory apparatuses. In Chapter 4, I examined a different sort of laboratory experience: a practical laboratory for project management. Through this study, I showed that the experience of a project manager in the course was comprehensively explored the skills in the PMBOK (PMI, 2013) and representative of my experience as a project manager in industry.

Chapters 2 and 4 illustrate implementations of Kolb’s (2014) cycle of experiential learning. Chapter 3 identifies objectives and other details necessary to begin designing a laboratory based on experiential learning.

In all three studies, I also noted the lack of clear assessment tools available to determine of the attainment of student learning outcomes as the result of an experience. In Chapter 2, the data I collected provided some assessment of the attainment of the learning outcomes stated in the research question, however it did not accurately reflect other skills learned in the laboratory such as MathWorks software, tuning, and problem solving. In Chapter 4, the assessment used provided some insight into areas of the PMBOK that we experienced; however, there was not a similar assessment during the course that all project managers completed. For project management students, the Certified Associate Project Management Professional exam administered by PMI (2015) might be an appropriate assessment. Assessment provides feedback to students and faculty about the effectiveness of the experience. Data from assessment can be used to provide grades for
students and as inputs for continuous improvement. The data can also be used to support updates or changes to the design of the laboratory experience itself so that it can support stronger learning outcomes.

Experiential learning is an integral part of engineering education. However, accurate assessment of student learning outcomes is also important. In my future work, I would like to develop more accurate assessment of the skills obtained and the achievement of other student learning outcomes in laboratories and projects in engineering education.

I would also like to create additional attachments for the affordable kit and develop additional affordable systems for advanced control systems and mechatronics courses. Additionally, I would like to explore opportunities to deploy a kit in an online course. Another possible direction is development of demonstrations or simulations that help students understand the practical applications of the complex mathematics and theories of control systems.
Academic Senate (2015). Committee on courses of instruction handbook part 2 — academic senate.


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PMI (2013). Organizational influences and project life cycle. *A guide to the project management body of knowledge (PMBOK guide)*, pages 18–45.


PMI (2016). Learn more about who PMI is and what we do.


Walther, J. & Sochacka, N. (2014). Qualifying qualitative research quality (the q3 project): An interactive discourse around research quality in interpretive approaches to engineering education research. In *2014 IEEE Frontiers in Education Conference, FIE.*


Welch, B. L. (1938). The significance of the difference between two means when the population variances are unequal. *Biometrika, 29,* 350–362.


This appendix provides the survey items and focus group questions used in the GE 320 study described in Chapter 2. Each of the Likert survey items had the following choices: A. Strongly disagree B. Disagree C. Agree D. Strongly agree. The concept inventory is available upon request.

A.1 Likert survey items

Note: Each of the Likert survey items had the following choices:
A. Strongly disagree B. Disagree C. Agree D. Strongly agree

1. I am satisfied with the GE 320 laboratory.

2. I am satisfied with the laboratory equipment for GE 320.

3. The GE 320 laboratory covered enough content.

4. The GE 320 laboratory assignments challenged me.

5. The GE 320 laboratory assignments reinforced topics from lecture.

6. I understood the objectives of the GE 320 laboratory.

7. I achieved the objectives of the GE 320 laboratory.

8. The GE 320 laboratory equipment was easy to use.

9. The GE 320 laboratory helped me learn concepts discussed in lecture.

10. The GE 320 laboratory equipment was a distraction to learning the concepts from lecture.

11. I learned skills in the GE 320 laboratory that I could use in industry.

12. I did not learn anything in the GE 320 laboratory.
13. The GE 320 laboratory equipment aided my learning of course material.

14. I felt frustrated with the GE 320 laboratory equipment in more than half of the laboratory sessions.

15. The GE 320 laboratory met my expectations.

16. The GE 320 laboratory equipment met my expectations.

17. I would recommend that students use the same equipment I used in future GE 320 laboratories.

The GE 320 laboratory (this includes the pre-lab questions, experiments, and post-lab questions, but does not include homework assignments or lectures) helped me learn the following topics:

1. Circuits
2. Laplace transforms
3. System identification
4. Types of controls
5. System stability
6. Design of control systems
7. MATLAB and Simulink
8. Design of PID controls
9. Design of lead-lag controls
10. Frequency Response

It was easy to understand how to complete the following tasks with the GE 320 laboratory equipment:

11. Tune the sensors used to measure speed and position of the motor

12. Identify the plant (system) to be controlled using first principles (measuring armature resistance, inductance, etc.)
13. Identify the plant (system) to be controlled using step response

14. Identify the plant (system) to be controlled using frequency response

15. Design various PID controllers

16. Implement PID controllers with the real motor

17. Test the PID controllers with the real motor

A.2 Open response survey questions

1. What did you like best about the laboratory equipment you used? Why?

2. What changes to the laboratory equipment would have improved your laboratory experience? Why?

3. What suggestions do you have for the laboratory instructions? Why?

4. Do you have any other comments about your overall laboratory experience? Why?

A.3 Focus group questions

1. What are your name, year in college, and current major?

2. Which concepts presented in lecture did the laboratory help you learn? How did the laboratory assignments help?

3. Which concepts presented in lecture did the laboratory not help you learn? How did the laboratory assignments hinder your learning?

4. What aspects of the laboratory equipment were easy or difficult to use?

5. What did you like about the laboratory equipment? Dislike?

6. What would you suggest be changed in the lab? Stay the same?

7. What was your favorite part of the GE 320 laboratory? Least favorite?
This appendix provides details on each of the survey instruments used in the study to determine common aspects of undergraduate control systems laboratories. Also, additional data and charts from each survey are provided to support the results presented in Chapter 3.

B.1 Delphi survey, round 1

This section describes the first round of the Delphi process.

B.1.1 Demographics

Note: if statements at the beginning of questions were be implemented through logic in Qualtrics.

1. At which university do you teach control systems?*
   
   One line text box.

2. In which department(s) do you teach control systems?*
   
   One line text box.

3. Are control systems courses required in your department(s)?
   
   (a) Yes
   
   (b) No
   
   (c) For some students/tracks

4. If Q3 is a or c, How many courses are required?
   
   (a) 1
   
   (b) 2
5. What level of control systems courses do you teach? (check all that apply)
   (a) Freshman
   (b) Sophomore
   (c) Junior
   (d) Senior
   (e) Graduate

6. Do your control systems courses have a laboratory component?
   (a) Yes, with physical systems
   (b) Yes, with simulation
   (c) Yes, both physical systems and simulation
   (d) No
   (e) Other (with one line text box)

7. Do you use the same laboratory space for all of your control systems courses?
   (a) Yes
   (b) No, we have multiple laboratory spaces
   (c) None of our control systems use laboratory space

8. Are you currently using low-cost hardware (e.g. Arduino, Raspberry Pi) in your control systems courses? Note: For the purpose of this study, low-cost hardware is defined as a microcontroller, single-board computer, or similar device that costs less than $300.
   (a) Yes
   (b) No
   (c) Some
   (d) N/A
9. If Q8 is a or c, Please tell us which one and describe how it is used in your courses.
   Open paragraph response

10. If Q8 is a or c, Were there any issues or limitations that you encountered with the low-cost hardware?
   Open paragraph response

11. If Q8 is a or c, If we have follow up questions about how you use low-cost hardware, may we follow up with you?
   (a) Yes
   (b) No

B.1.2 Main survey

When answering the following questions, imagine that you are building a new control systems laboratory from the ground up and you have a budget of only $400/station (the cost does not need to include software or a PC).

1. What are the most important learning outcomes (e.g. the ability to tune a controller to meet specifications, the ability to implement a specific controller, the ability to communicate results) of your control systems laboratory?*

2. What are the most important control systems related concepts for students to learn or be able to demonstrate during a control systems laboratory?*

3. What are the most important equipment/tools/software for the students to experience during a control systems laboratory?*

Please provide your name and email address so that we can send reminders for each of the following phases of the survey.

1. Name*
   One line text box.

2. Email*
   One line text box.
Thank you for your time, the next round will be open from July 20-31.

*Required questions

### B.2 Delphi survey, round 2

Note: Each item was implemented in Qualtrics with a slider from one to ten, with one being very low importance and ten being very high importance. Panelists were required to rate each item. A screen shot of the Qualtrics interface for these items is provided in Figure B.1

![Figure B.1: Screen shot of round 2 from Qualtrics.](image-url)
When answering the questions in this round, imagine that you are building a new control systems laboratory from the ground up and you have a budget of only $400/station (the cost does not need to include software or a PC).

What are the most important learning outcomes (e.g. the ability to tune a controller to meet specifications, the ability to implement a specific controller, the ability to communicate results) of your control systems laboratory?

1. Model and simulate a system
2. Perform system identification using data obtained in the laboratory
3. Identify differences between models and physical systems
4. Recognize the tradeoffs between simplifying a system model and being accurate enough to design a controller
5. Design and verify a controller meets specifications
6. Implement a controller learned in lecture
7. Tune a controller
8. Tune a controller while it is running
9. Compare controllers and select the appropriate controller for the provided system
10. Connect theory to what is implemented and observed in the laboratory
11. Collect and visualize input and output data
12. Find errors and correct for them (debugging)
13. Identify practical issues that arise with physical systems such as sensor noise, interference, saturation, and large gains
14. Write a laboratory report that includes topics like design, experimental procedures, results, and analysis
15. Design laboratories and do undergraduate research
What are the most important control systems related concepts for students to learn or be able to demonstrate during a control systems laboratory?

1. Closed loop vs. open loop control
2. PID Control
3. Compensators including lead and/or lag control
4. Tracking and disturbance rejection
5. Observability and observer design
6. Adaptive control
7. Ziegler-Nichols
8. Ladder logic
9. Continuous-time
10. Discrete-time
11. Pole/Zero plots
12. Root locus
13. Bode plot
14. Bandwidth, peak value, and peak frequency
15. Phase and gain margins, phase and gain crossover frequencies
16. Frequency response
17. Maximum overshoot or percent overshoot, rise time, settling time, and steady-state error
18. Damping ratio and undamped natural frequency
19. Step response
20. Laplace transforms
21. Transfer functions
22. Block diagram representation of a system

23. State-space

24. Stability

25. System order reductions and other modeling approximations, such as only using dominate poles

26. Nonlinear characteristics, such as the effects of friction

What are the most important equipment/tools/software for the students to experience during a control systems laboratory?

1. LabVIEW

2. Mathworks including MATLAB, Simulink, SISO Tool, and QUARK

3. Programming languages including C and Python

4. Microcontrollers including Arduino or embedded systems

5. Programmable logic controllers (PLCs)

6. Electro-Mechanical systems including servos or motors

7. Mechanical systems including spring-mass-damper, actuators, or hydraulics

8. Electrical systems including first and second order circuits

9. Fluid or thermal systems including temperature or liquid level in tanks

10. Physical lab bench equipment including power supply, function generator, multimeter, oscilloscope, spectrum analyzer

11. Virtual or simulated lab bench equipment including power supply, function generator, multimeter, oscilloscope, spectrum analyzer

12. Data acquisition

13. Tools representative of industry
14. Digital and analog I/O

15. A/D and D/A conversion

Please provide your name and email address so that we can send reminders for each of the following phases of the survey.

1. Name*
   One line text box.

2. Email*
   One line text box.

Thank you for your time, the next round will be open from August 3-14.

*Required questions

B.3 Delphi survey, round 3

The survey in round 3 looked like round 2 with two exceptions. First, the mean and IQR from round 2 were included with the item above each slider bar. The mean and IQR from round 2 are included in Tables B.1-B.4. Second, using the logic built into Qualtrics, the panelist was presented with open paragraph text boxes for each item they rated outside of the IQR on the next screen.

B.4 Delphi survey, round 4

The survey in round 4 was similar to round 2 and round 3. However, instead of one block of slider bars for ratings. Each item had its own slider bar with the median, IQR, and the anonymized comments provided by panelists in round 3 in the description. This section provides the round 3 median, IQR, and representative comments for each item.

B.4.1 Objectives

1. Model and simulate a system, Mean = 8.17, IQR = 8-9
   Comments (with ratings in parentheses):
   
   • We do that in theory classes - in labs we focus on experiments (3)
2. Perform system identification using data obtained in the laboratory, Mean = 6.9, IQR = 6-8
Comments (with ratings in parentheses):

- System identification is extremely valuable in many respects. [1] Real-world systems are generally far too complex for analytically generating a system model, thus system ID is used. [2] System ID helps students understand s-domain system represent (10)

3. Identify differences between models and physical systems, Mean = 7.93, IQR = 7-9
Comments (with ratings in parentheses):

- Not what a Community College does (3)
- It is important that students understand the difference between the models in labs and actual physical system. It is not easy to build an physical systems due to many reasons but it is important to develop a model connecting the theory and practical. (10)
- Students need to understand that physical systems are different from models and they need to learn how to deal with these differences when implementing control systems. (10)
- I rested this a 10 because it implies the students understand the assumptions they are making to simplify the model of the physical system. Very important! (10)
- Understanding nonlinearities and how they make real behavior different than that assumed by classical (linear) controls is an absolutely essential skill. (10)

4. Recognize the tradeoffs between simplifying a system model and being accurate enough to design a controller, Mean = 7.27, IQR = 6.25-8
Comments (with ratings in parentheses):

- Not what a Community College does (3)
- The general concept here is very of the core of Engineering practice that is not stressed in education. Specifically, in the control systems area, the text books focus on forming "tractable" problems giving very detailed specifications. (9)
- I think it is fundamental that engineering students develop a mindset that engineering is never exact. They need to learn to balance the level of work it takes to develop a good model with how important this model actually is. (9)
5. Design and verify a controller meets specifications, Mean = 8.27, IQR = 8-9
   Comments (with ratings in parentheses):
   - I think this over stressed in most courses and texts. It is more important to optimize
     the controller in a few basic ways that are not easily “specified.” For example optimize
     low frequency gain when tracking is important. (5)
   - System identification and modeling are hugely important, but the goal is to get to
     designing systems. (10)

6. Implement a controller learned in lecture, Mean = 7.8, IQR = 7-9
   Comments (with ratings in parentheses):
   - I assume this means implementing a controller given by the instructor. I want students
     to do their own implementation. (5)
   - I can exercise a lot of introductory controls concepts with a proportional or PID con-
     troller without getting into more complex controller types. (6)
   - It is important that student connect the theory to lab, they should get a chance to build
     a controller taught in theory and implement and understand the errors. (10)

7. Tune a controller, Mean = 7.6, IQR = 7-8
   Comments (with ratings in parentheses):
   - I rated the question a 6, because this skill is not adequately able to be mastered in a
     two-year program, i.e., it is only introduced and discussed. (6)
   - If they design and implement a controller that meets the specifications, I would say they
     have ‘tuned it’. I understood the design to be an iterative process, but perhaps that’s
     what you meant by ‘tune’ (6)
   - It is not really useful to implement a control system without tuning it to understand-
     ing how gains impact the controller’s performance. For example, implementing a PID
     controller without learning how to tune it isn’t very useful. (10)

8. Tune a controller while it is running, Mean = 5.6, IQR = 4.25-7
   Comments (with ratings in parentheses):
• Adjusting controller gains while a system is running can make the tuning process clearer. Making adjustments while a system is not running, then running it, and repeating the process can be tedious and more difficult to understand. (8)

9. Compare controllers and select the appropriate controller for the provided system, Mean = 6.83, IQR = 6.25-8

Comments (with ratings in parentheses):

• Not too important for undergrad controls. Rather keep them focus and master one type of controller design and implementation, such as PID. (5)

10. Connect theory to what is implemented and observed in the laboratory, Mean = 9, IQR = 8-10

Comments (with ratings in parentheses):

• It is often very difficult to transfer the theory of control systems to practical experiments with a limited budget. It can be done to some degree, but there are limitations. (7)

11. Collect and visualize input and output data, Mean = 8, IQR = 8-8.75

No comments

12. Find errors and correct for them (debugging), Mean = 6.93, IQR = 6-7

Comments (with ratings in parentheses):

• I see debugging as a useful exercise, but I usually try to minimize how much of it the students have to do in the lab, because they lose time that they could be spending on learning the subject matter. (5)

• A controller with errors that go unfixed is almost useless. Unless you are teaching students to depend on someone else's auto-code generation tool, they need to know how to debug to make anything that is practically useful. (9)

13. Identify practical issues that arise with physical systems such as sensor noise, interference, saturation, and large gains, Mean = 7.83, IQR = 7-8

Comments (with ratings in parentheses):

• We do want to touch upon these issues but not required to be extensive. In our labs, we do point out the effect and limitations of saturation, noise, and dynamic range. (6)
• If we just wanted to teach them theory, then why do experiments? Bumping into practical issues is a big reason to do experiments. I don’t want to develop unpractical control engineers. The world has enough theorists in it. (9)

• I’m more concerned with saturation and sensor noise than interference (mechanical engineering). Designing a controller that works in simulation is only half the task. If it can’t be implemented, it’s still junk. (10)

14. Write a laboratory report that includes topics like design, experimental procedures, results, and analysis, Mean = 6.8, IQR = 6-8

Comments (with ratings in parentheses):

• I don’t put much importance on writing lab reports partially because that is covered elsewhere in our curriculum. It seems that when we stress that it becomes THE focus because the students are so concerned with getting the points for the report. (5)

• I rated this a 10 because communicating an idea, tests of that idea, and results of the tests is very important in engineering. Especially if the solution must meet design criteria. (10)

15. Design laboratories and do undergraduate research, Mean = 4.2, IQR = 3-5

Comments (with ratings in parentheses):

• I don’t care if the students are able to design laboratories. Undergrad research is for a handful of students for whom I can provide smaller numbers of much more capable lab equipment. (1)

• We forget that the only way we can have good graduate program is seed research skill in undergraduate students. (10)

B.4.2 Concepts

1. Closed loop vs. open loop control, Mean = 8.07, IQR = 8-9

Comments (with ratings in parentheses):

• Covered in class, rather obvious so not as important (5)

2. PID Control, Mean = 8.73, IQR = 8-9

Comments (with ratings in parentheses):
• Not what a Community College does (2)

• I think 7 out of 10 reflects the importance of PID control without overrating it. (7)

• PID is not as important as lead/lag. It has an extra degree of freedom that makes design more difficult. (7)

3. Compensators including lead and/or lag control, Mean = 6.5, IQR = 5-8

Comments (with ratings in parentheses):

• Our lab in an introductory lab, so we don’t get to this topic (3)

• PID control is powerful, but pretty basic. Understanding compensator design can help students take the next steps in performance and complexity. (9)

4. Tracking and disturbance rejection, Mean = 7, IQR = 6-8

Comments (with ratings in parentheses):

• Our lab in an introductory lab, so we don’t get to this topic (3)

• Disturbances are a primarily reason why we need closed-loop control in the first place, so it’s important to know how to handle them. (9)

5. Observability and observer design, Mean = 4.87, IQR = 3-6

Comments (with ratings in parentheses):

• I consider this outside the scope of an undergraduate introductory controls class. (1)

• Not important for my undergrads, but I’d like my grad students (500 level) to see it. (8)

6. Adaptive control, Mean = 2.87, IQR = 2-4

Comments (with ratings in parentheses):

• I consider this outside the scope of an undergraduate introductory controls class. (1)

7. Ziegler-Nichols, Mean = 3.7, IQR = 2-5

Comments (with ratings in parentheses):

• Ziegler-Nichols is extremely difficult to get usable results from. Worthless in my estimation (1)

• Because of its practical value/use in industry. It’s a widely used technique. (10)
8. Ladder logic, Mean = 2.7, IQR = 1-3.75
   Comments (with ratings in parentheses):
   - Ladder logic and plcs are a key component of the outcomes at my institution. (8)
   - My students are several times more likely to use this in industrial experience than classical controls. I have a separate PLC lab for this. (10)

9. Continuous-time, Mean = 7.4, IQR = 6.25-9
   Comments (with ratings in parentheses):
   - Most systems are implemented in discrete time domain. (5)

10. Discrete-time, Mean = 5.5, IQR = 5-7
    Comments (with ratings in parentheses):
    - Not covered in the first controls course; DSP and signals & systems are taken at the same time or after the controls course (2)

11. Pole/Zero plots, Mean = 7.53, IQR = 6.25-9
    Comments (with ratings in parentheses):
    - Not what a Community College does (2)

12. Root locus, Mean = 7.27, IQR = 6.25-8
    Comments (with ratings in parentheses):
    - Not what a Community College does (2)

13. Bode plot, Mean = 7.83, IQR = 7-9
    No comments

14. Bandwidth, peak value, and peak frequency, Mean = 6.4, IQR = 5.25-7
    Comments (with ratings in parentheses):
    - Covered in the analog electronics course (2)
    - These are simple but important system characteristics that are easy to demonstrate in a laboratory. They are also critical to student understanding of data acquisition, filtering, etc. (9)
15. Phase and gain margins, phase and gain crossover frequencies, Mean = 6.83, IQR = 6-8

Comments (with ratings in parentheses):

- Covered late in lecture; not enough time to cover in lab (2)
- Find students learn via root locus better (4)
- The absolute most effective design concepts. (9)

16. Frequency response, Mean = 7.87, IQR = 7-9

Comments (with ratings in parentheses):

- Find students learn via root locus better (5)
- Frequency response is important but I don’t spend much time on it because most practical control system designs do not require measuring and designing with FR, especially PID type systems. (6)

17. Maximum overshoot or percent overshoot, rise time, settling time, and steady-state error, Mean = 8.57, IQR = 8-9

Comments (with ratings in parentheses):

- Overemphasized and used as detailed specifications. However, calculating these for systems with zeros and anything beyond 2nd order systems is not tractable. (6)

18. Damping ratio and undamped natural frequency, Mean = 8.5, IQR = 8-9

Comments (with ratings in parentheses):

- Easy to convey these ideas so not much emphasis is needed (6)

19. Step response, Mean = 8.97, IQR = 9-10

Comments (with ratings in parentheses):

- They are easy concepts that don’t need too much time IMO, and (except for SSO) probably are not extremely relevant in control design. (6)

20. Laplace transforms, Mean = 8.2, IQR = 8-9

Comments (with ratings in parentheses):
• Laplace transforms are the underlying mathematics to transfer functions and modeling of time dependent systems. I think they are as important as differential equations to control systems and engineers working in this area. (10)

21. Transfer functions, Mean = 8.87, IQR = 8-10
   Comments (with ratings in parentheses):
   • Not what a Community College does (2)

22. Block diagram representation of a system, Mean = 9.07, IQR = 8.25-10
   No comments

23. State-space, Mean = 6.17, IQR = 5-8
   Comments (with ratings in parentheses):
   • You do not need state space to understand frequency response, root locus, and SISO design methods. If the student never takes another control class, what do you want the student to remember from the class? (3)
   • Because this course at [SCHOOL] is a pre-requisite to Aircraft Stability and Controls which requires good understanding of state-space model of systems. (9)

24. Stability, Mean = 8.9, IQR = 8-9.75
   Comments (with ratings in parentheses):
   • Not what a Community College does (2)

25. System order reductions and other modeling approximations, such as only using dominate poles, Mean = 6.07, IQR = 5-7
   Comments (with ratings in parentheses):
   • Lack of time in class. (4)
   • Students need to understand what they are doing and when it is appropriate to use a simpler model or to design based on system response to a simpler model. (8)

26. Nonlinear characteristics, such as the effects of friction, Mean = 6.17, IQR = 5-8
   Comments (with ratings in parentheses):
• This is too big of a topic for my students to understand in the time I have with them for this class. (3)
• A key aspect of taking things into real implementation (9)

B.4.3 Laboratory components

1. LabVIEW, Mean = 4.13, IQR = 2-5.75
   Comments (with ratings in parentheses):
   • I have had many bad experiences with it (1)
   • I find LabView to be a great option for some applications. Nice for advanced students to see that there are additional tools. (8)

2. Mathworks including MATLAB, Simulink, SISO Tool, and QUARK, Mean = 8.67, IQR = 8-9.75
   Comments (with ratings in parentheses):
   • Teaching our students to depend on expensive tools when there are good, free alternatives is not best. Further, too much dependence on certain tools can impede students from thinking for themselves. (4)

3. Programming languages including C and Python, Mean = 4, IQR = 2-5
   Comments (with ratings in parentheses):
   • We use Matlab / Simulink (1)
   • A lot of really important learning takes place when you code things up on a microcontroller. That pretty much has to be done in C. Python is a phenomenal language. I encourage students to use it whenever I can. (9)

4. Microcontrollers including Arduino or embedded systems, Mean = 5.4, IQR = 3.25-7
   Comments (with ratings in parentheses):
   • For EE’s that may be important, but for ME’s it really isn’t as significant. (2)
   • I want to help students build small robots and other things. Microcontrollers are essential for mobile robots. If we only teach them to use very expensive hardware, we are doing a disservice to our students. (9)
5. Programmable logic controllers (PLCs), Mean = 3.4, IQR = 2-5
   Comments (with ratings in parentheses):
   
   • I don’t think they are important for engineers that likely won’t work in a manufacturing environment. (1)
   • My students are several times more likely to employ PLCs in their careers than classical control theory. I have a separate PLC lab for this. (10)

6. Electro-Mechanical systems including servos or motors, Mean = 8.57, IQR = 8-9
   Comments (with ratings in parentheses):
   
   • All the options were important, AND others so I ranked them all the same (5)

7. Mechanical systems including spring-mass-damper, actuators, or hydraulics, Mean = 8, IQR = 8-9
   Comments (with ratings in parentheses):
   
   • This course is taught in the EE program; motors (electromechanical systems) are the focus of the lab (5)
   • These are simple and inexpensive components that can be used to illustrate a broad range of control system topics, while also lending themselves to theoretical modeling. (10)

8. Electrical systems including first and second order circuits, Mean = 7.3, IQR = 7-8
   Comments (with ratings in parentheses):
   
   • All the options were important, AND others so I ranked them all the same (5)
   • One way or another, Mechanical Engineers will have to deal with electrical circuits. Also, they can be very important for data acquisition from sensors or other sources, for filters, etc. when dealing with noisy equipment and physical hardware. (9)

9. Fluid or thermal systems including temperature or liquid level in tanks, Mean = 5.5, IQR = 4-7
   Comments (with ratings in parentheses):
   
   • This is an application example that is unnecessary in an introductory controls course. (3)
• These are simple and inexpensive components that can be used to illustrate a broad range of control system topics, while also lending themselves to theoretical modeling. (9)

10. Physical lab bench equipment including power supply, function generator, multimeter, oscilloscope, spectrum analyzer, Mean = 6.4, IQR = 5-8

Comments (with ratings in parentheses):

• I think tools like the Digilent Electronics board with software that runs on a computer is just fine for most undergraduate students, and they do not need the expense of the other equipment. Also it allows the labs to be more portable. (2)
• I’m a big proponent of hardware. Simulation is great, but hardware is ultimately what matters. Students should be capable of working with physical systems, including physical testing equipment. (10)

11. Virtual or simulated lab bench equipment including power supply, function generator, multimeter, oscilloscope, spectrum analyzer, Mean = 4.27, IQR = 2.25-5

Comments (with ratings in parentheses):

• Not what a Community College does (1)
• Students should learn to use basic equipment (7)
• we use virtual instrumentation for the electromechanical and controls courses. (7)
• In the absence of actual bench instruments, students must have access to some form of test equipment to analyze system behavior. This can be considerably less expensive (given that you have LabVIEW or something similar) than buying equipment. (8)

12. Data acquisition, Mean = 7, IQR = 6-8

Comments (with ratings in parentheses):

• Not what a Community College does (1)
• Control systems are based on the acquisition of some type of signal that represents the current state of the system...data acquisition. It is a critical skill for implementing control systems in physical hardware and can be done inexpensively. (10)
13. Tools representative of industry, Mean = 7.5, IQR = 7-8

Comments (with ratings in parentheses):

- Not what a Community College does (1)
- In the end, most students will go on to industry instead of graduate school. A key responsibility of the controls laboratory is to expose students to tools they may be using in professional practice. (10)

14. Digital and analog I/O, Mean = 6.8, IQR = 6-8

Comments (with ratings in parentheses):

- Control systems are based on the acquisition of some type of signal that represents the current state of the system...data acquisition of analog or digital signals. Then, the system must be controlled using analog or digital outputs. (10)

15. A/D and D/A conversion, Mean = 6.27, IQR = 5.25-7

Comments (with ratings in parentheses):

- This topic is covered more fully in an Instrumentation class at my university and I spend very little time on it in my Controls class. (2)
- Understanding A/D and D/A is central to data acquisition and generation of control signals. (10)

B.5 Follow-up survey

This section describes the follow-up survey and the implementation in Qualtrics.

B.5.1 Demographics

1. First Name
   One line text box.

2. Last Name
   One line text box.

3. Do you consider your primary role as a:
(a) Faculty member

(b) Practitioner

4. If Q3 is b, Have you ever taught a control systems course at a college or university?

(a) Yes, currently

(b) Yes, within the last 1-3 years

(c) Yes, within the last 3-5 years

(d) Yes, more than 5 years ago

(e) No

5. If Q3 is b, What industry do you work in?

a. Food, Beverage or Tobacco

b. Textiles or Apparel

c. Wood, Paper or Printing

d. Petroleum or Refining

e. Chemicals

f. Pharmaceuticals

g. Plastics or Rubber

h. Primary or Fabricated Metals

i. Industrial Machinery


k. Engine, Turbine, Mechanical or Electrical Power Transmission Equipment

l. Computer Systems or Peripherals

m. Communications Systems or Equipment

n. Consumer Electronics or Appliances

o. Semiconductors or Other Electronics Components

p. Industrial Controls, Test or Medical Equipment

q. Instrumentation, Measurement or Control Systems or Devices
r. Electrical Equipment
s. Aircraft, Aerospace or Defense
t. Automotive or Transportation
u. Mining, Agriculture or Construction
v. Utilities or Telecommunications
w. Engineering or System Integration Services
x. Scientific or Research Services
y. Information, Data Processing or Software Services
z. Consulting, Business or Technical Services
aa. Government or Military
bb. Other Manufacturing
cc. Other Non-Manufacturing

B.5.1.1 Teaching

Note: This section was only displayed to participants who selected Faculty on question 3 or Practitioner on Question 3 and not No on Question 4.

1. At which college or university do you teach (or have taught) control systems?*
   One line text box.

2. For which major(s) do you teach (or have taught) control systems? Check all that apply*

   (a) Electrical Engineering
   (b) Mechanical Engineering
   (c) Aeronautical/Aerospace Engineering
   (d) Nuclear Engineering
   (e) Biomedical Engineering
   (f) Engineering/General Engineering
   (g) Industrial Engineering
   (h) Systems Engineering
3. Are control systems courses required in your department(s)?
   
   (a) Yes
   (b) No
   (c) For some students/tracks

4. If a or c was selected in the previous question, How many courses are required?
   
   (a) 1
   (b) 2
   (c) 3
   (d) 4 or more

5. What level of control systems courses do you teach (or have taught)? (check all that apply)
   
   (a) Freshman
   (b) Sophomore
   (c) Junior
   (d) Senior
   (e) Graduate

6. Do your control systems courses have a laboratory component?
   
   (a) Yes, with physical systems
   (b) Yes, with simulation
   (c) Yes, both physical systems and simulation
   (d) No
7. Do you use the same laboratory space for all of your control systems courses?

(a) Yes
(b) No, we have multiple laboratory spaces
(c) None of our control systems use laboratory space

B.5.2 Main survey

B.5.2.1 Implementation notes

- Each item was implemented in Qualtrics with a slider from one to ten, with one being very low importance and ten being very high importance. Participants were required to rate each item. A screen shot of the Qualtrics interface for these items is provided in Figure B.1.

- If a practitioner indicated they had never taught a control systems course, the following additional instruction was displayed:

> Please answer the following questions based on your expectations for what experience graduates entering your industry should have.

B.5.2.2 Survey text

In the summer of 2015, forty experts in control systems completed multiple rounds of surveys to arrive at consensus answers to the following questions:

1. What are the most important learning outcomes (e.g. the ability to tune a controller to meet specifications, the ability to implement a specific controller, the ability to communicate results) of your control systems laboratory?

2. What are the most important control systems related concepts for students to learn or be able to demonstrate during a control systems laboratory (e.g. Bode Plots, PID control, Step Response)?

3. What are the most important equipment/tools/software for the students to experience during a control systems laboratory?
The results of this process are presented here to validate these results and receive comments from a larger proportion of control systems community.

Note: In the interest of time you will be asked to respond to question 1 and either question 2 or 3

B.5.2.2.1 Results of question 1. What are the most important learning outcomes (e.g. the ability to tune a controller to meet specifications, the ability to implement a specific controller, the ability to communicate results) of your control systems laboratory?

Rate each of the following learning outcomes on a 1-10 scale, where 1 is the low importance and 10 is high importance.

1. Model and simulate a system
2. Perform system identification using data obtained in the laboratory
3. Identify differences between models and physical systems
4. Recognize the tradeoffs between simplifying a system model and being accurate enough to design a controller
5. Design and verify a controller meets specifications
6. Implement a controller learned in lecture
7. Tune a controller
8. Tune a controller while it is running
9. Compare controllers and select the appropriate controller for the provided system
10. Connect theory to what is implemented and observed in the laboratory
11. Collect and visualize input and output data
12. Find errors and correct for them (debugging)
13. Identify practical issues that arise with physical systems such as sensor noise, interference, saturation, and large gains
14. Write a laboratory report that includes topics like design, experimental procedures, results, and analysis
15. Design laboratories and do undergraduate research

Do you have any additional comments or concerns about the above list?
Open paragraph response.
How do you assess laboratory learning outcomes?
Open paragraph response.

**B.5.2.2.2 Results of question 2.** What are the most important control systems related concepts for students to learn or be able to demonstrate during a control systems laboratory (e.g. Bode Plots, PID control, Step Response)?

By the end of an undergraduate control systems laboratory students will have applied the following concepts:

Rate each of the following learning outcomes on a 1-10 scale, where 1 is the low importance and 10 is high importance.

1. Closed loop vs. open loop control
2. PID Control
3. Tracking and disturbance rejection
4. Pole/Zero plots
5. Root locus
6. Bode plot
7. Bandwidth, peak value, and peak frequency
8. Phase and gain margins, phase and gain crossover frequencies
9. Frequency response
10. Maximum overshoot or percent overshoot, rise time, settling time, and steady-state error
11. Damping ratio and undamped natural frequency
12. Step response
13. Laplace transforms
14. Transfer functions

15. Block diagram representation of a system

16. Stability

Do you have any additions to the above list?

Do you have any additional comments or concerns about the above list?

B.5.2.2.3 Results of question 3. What are the most important equipment/tools/software for the students to experience during a control systems laboratory?

By the end of an undergraduate control systems laboratory students will have gained experience using the following equipment/tools/software ...

Rate each of the following learning outcomes on a 1 -10 scale, where 1 is the low importance and 10 is high importance.

1. LabVIEW

2. Mathworks including MATLAB, Simulink, SISO Tool, and QUARK

3. Programming languages including C and Python

4. Microcontrollers including Arduino or embedded systems

5. Programmable logic controllers (PLCs)

6. Electro-Mechanical systems including servos or motors

7. Mechanical systems including spring-mass-damper, actuators, or hydraulics

8. Electrical systems including first and second order circuits

9. Fluid or thermal systems including temperature or liquid level in tanks

10. Physical lab bench equipment including power supply, function generator, multimeter, oscilloscope, spectrum analyzer
11. Virtual or simulated lab bench equipment including power supply, function generator, multimeter, oscilloscope, spectrum analyzer

12. Data acquisition

13. Tools representative of industry

14. Digital and analog I/O

15. A/D and D/A conversion

Do you have any additional comments or concerns about the above list?
Open paragraph response.

Do you have any other comments or suggestions for undergraduate control systems instructional laboratories?
Open paragraph response.

B.5.3 Additional Questions

1. How did you hear about this survey? Check all that apply.

   (a) Email from an IEEE Society
   (b) Email from an ASEE Division
   (c) Email from an ASME Division
   (d) LinkedIn
   (e) Facebook
   (f) Twitter
   (g) Word of mouth
   (h) Other

2. Do you have any other questions or comments for the researchers?
Open paragraph response.

3. Please provide your email address if you would like the researchers to follow up with you.
One line text box.
B.6 Additional survey data

B.6.1 Objectives
<table>
<thead>
<tr>
<th>Item</th>
<th>Round 2</th>
<th>Round 3</th>
<th>Round 4</th>
<th>Follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$</td>
<td>$IQR$</td>
<td>$M$</td>
<td>$IQR$</td>
</tr>
<tr>
<td>1. Model and simulate a system</td>
<td>8.41</td>
<td>8−10</td>
<td>8.17</td>
<td>8−9</td>
</tr>
<tr>
<td>2. Perform system identification using data obtained in the laboratory</td>
<td>6.88</td>
<td>5−8</td>
<td>6.9</td>
<td>6−8</td>
</tr>
<tr>
<td>3. Identify differences between models and physical systems</td>
<td>7.5</td>
<td>6−9</td>
<td>7.93</td>
<td>7−9</td>
</tr>
<tr>
<td>4. Recognize the tradeoffs between simplifying a system model and being accurate enough to design a controller</td>
<td>7.15</td>
<td>6−8</td>
<td>7.27</td>
<td>6.25−8</td>
</tr>
<tr>
<td>5. Design and verify a controller meets specifications</td>
<td>8.26</td>
<td>7.25−9</td>
<td>8.27</td>
<td>8−9</td>
</tr>
<tr>
<td>6. Implement a controller learned in lecture</td>
<td>7.76</td>
<td>7−9</td>
<td>7.8</td>
<td>7−9</td>
</tr>
<tr>
<td>7. Tune a controller</td>
<td>7.32</td>
<td>7−8</td>
<td>7.6</td>
<td>7−8</td>
</tr>
<tr>
<td>8. Tune a controller while it is running</td>
<td>5.24</td>
<td>3−7</td>
<td>5.6</td>
<td>4.25−7</td>
</tr>
<tr>
<td>9. Compare controllers and select the appropriate controller for the provided system</td>
<td>6.65</td>
<td>6−8</td>
<td>6.83</td>
<td>6.25−8</td>
</tr>
<tr>
<td>10. Connect theory to what is implemented and observed in the laboratory</td>
<td>8.82</td>
<td>8−10</td>
<td>9</td>
<td>8−10</td>
</tr>
<tr>
<td>11. Collect and visualize input and output data</td>
<td>7.56</td>
<td>6−9</td>
<td>8</td>
<td>8−8.75</td>
</tr>
<tr>
<td>12. Find errors and correct for them (debugging)</td>
<td>6.65</td>
<td>5.25−8</td>
<td>6.93</td>
<td>6−7</td>
</tr>
<tr>
<td>13. Identify practical issues that arise with physical systems</td>
<td>7.56</td>
<td>7−8</td>
<td>7.83</td>
<td>7−8</td>
</tr>
<tr>
<td>14. Write a laboratory report</td>
<td>6.44</td>
<td>5.25−8</td>
<td>6.8</td>
<td>6−8</td>
</tr>
<tr>
<td>15. Design laboratories and do undergraduate research</td>
<td>4.88</td>
<td>3−7</td>
<td>4.2</td>
<td>3−5</td>
</tr>
</tbody>
</table>
Figure B.2: Bar chart of average ratings for each objective from Delphi rounds 2-4 and the follow-up survey.
Figure B.3: Scatter plot of average ratings for each objective from Delphi round 4 vs. the follow-up survey.
B.6.2 Concepts

Table B.2: Additional statistics for first half of concept items.

<table>
<thead>
<tr>
<th>Item</th>
<th>Round 2</th>
<th></th>
<th>Round 3</th>
<th></th>
<th>Round 4</th>
<th>Rank</th>
<th>IQR</th>
<th>%</th>
<th>Rank</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed loop vs. open loop control</td>
<td>7.79</td>
<td>7–9</td>
<td>8.07</td>
<td>8–9</td>
<td></td>
<td></td>
<td>8–8.25</td>
<td>94%</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>PID Control</td>
<td>8.56</td>
<td>8–10</td>
<td>8.73</td>
<td>8–9</td>
<td></td>
<td></td>
<td>8–9</td>
<td>94%</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Compensators</td>
<td>6.35</td>
<td>5–8</td>
<td>6.5</td>
<td>5–8</td>
<td></td>
<td></td>
<td>6–7.25</td>
<td>84%</td>
<td>16</td>
<td></td>
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<tr>
<td>Tracking and disturbance rejection</td>
<td>6.94</td>
<td>6–8</td>
<td>7</td>
<td>6–8</td>
<td></td>
<td></td>
<td>7–8</td>
<td>81%</td>
<td>13</td>
<td>8</td>
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<tr>
<td>Observability and observer design</td>
<td>4.88</td>
<td>3–7</td>
<td>4.87</td>
<td>3–6</td>
<td></td>
<td></td>
<td>3–6</td>
<td>42%</td>
<td>23</td>
<td></td>
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<tr>
<td>Adaptive control</td>
<td>3.91</td>
<td>2–5</td>
<td>2.87</td>
<td>2–4</td>
<td></td>
<td></td>
<td>2–3</td>
<td>77%</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Ziegler-Nichols</td>
<td>4.76</td>
<td>2–7</td>
<td>3.7</td>
<td>2–5</td>
<td></td>
<td></td>
<td>2–4</td>
<td>68%</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Ladder logic</td>
<td>3.68</td>
<td>1–6.75</td>
<td>2.7</td>
<td>1–3.75</td>
<td></td>
<td></td>
<td>1–4</td>
<td>52%</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Continuous-time</td>
<td>7.47</td>
<td>6–9</td>
<td>7.4</td>
<td>6.25–9</td>
<td></td>
<td></td>
<td>6–8</td>
<td>74%</td>
<td>15</td>
<td></td>
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<tr>
<td>Discrete-time</td>
<td>5.94</td>
<td>4.25–8</td>
<td>5.5</td>
<td>5–7</td>
<td></td>
<td></td>
<td>3.75–6</td>
<td>58%</td>
<td>22</td>
<td></td>
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<tr>
<td>Pole/Zero plots</td>
<td>6.79</td>
<td>5–9</td>
<td>7.53</td>
<td>6.25–9</td>
<td></td>
<td></td>
<td>6.75–8.25</td>
<td>71%</td>
<td>12</td>
<td>12</td>
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<td>Root locus</td>
<td>7.15</td>
<td>6–8</td>
<td>7.27</td>
<td>6.25–8</td>
<td></td>
<td></td>
<td>7–8</td>
<td>90%</td>
<td>14</td>
<td></td>
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<tr>
<td>Bode plot</td>
<td>7.53</td>
<td>6.25–9</td>
<td>7.83</td>
<td>7–9</td>
<td></td>
<td></td>
<td>7–8</td>
<td>94%</td>
<td>10</td>
<td>13</td>
</tr>
</tbody>
</table>
Table B.3: Additional statistics for second half of concept items.

<table>
<thead>
<tr>
<th>Item</th>
<th>Round 2</th>
<th></th>
<th>Round 3</th>
<th></th>
<th>Round 4</th>
<th></th>
<th>Follow-up</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>IQR</td>
<td>M</td>
<td>IQR</td>
<td>IQR</td>
<td>%</td>
<td>Rank</td>
<td>Rank</td>
</tr>
<tr>
<td>14. Bandwidth, peak value, and peak frequency</td>
<td>6.56</td>
<td>5–8.75</td>
<td>6.4</td>
<td>5.25–7</td>
<td>6–7.25</td>
<td>77%</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>15. Phase and gain margins, phase and gain crossover frequencies</td>
<td>6.94</td>
<td>6–8.75</td>
<td>6.83</td>
<td>6–8</td>
<td>6–7</td>
<td>77%</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>16. Frequency response</td>
<td>7.97</td>
<td>7–9</td>
<td>7.87</td>
<td>7–9</td>
<td>7–9</td>
<td>74%</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>17. Maximum percent overshoot, rise time, settling time, and steady-state error</td>
<td>8.29</td>
<td>7–10</td>
<td>8.57</td>
<td>8–9</td>
<td>8–9</td>
<td>84%</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>18. Damping ratio and undamped natural frequency</td>
<td>8</td>
<td>7–10</td>
<td>8.5</td>
<td>8–9</td>
<td>7.75–9</td>
<td>90%</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>19. Step response</td>
<td>8.71</td>
<td>8–10</td>
<td>8.97</td>
<td>9–10</td>
<td>8–9</td>
<td>87%</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>20. Laplace transforms</td>
<td>7.21</td>
<td>5–9</td>
<td>8.2</td>
<td>8–9</td>
<td>8–9</td>
<td>97%</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>21. Transfer functions</td>
<td>7.97</td>
<td>7–10</td>
<td>8.87</td>
<td>8–10</td>
<td>9–10</td>
<td>100%</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>22. Block diagram representation of a system</td>
<td>8.41</td>
<td>7–10</td>
<td>9.07</td>
<td>8.25–10</td>
<td>9–10</td>
<td>100%</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>24. Stability</td>
<td>8.56</td>
<td>8–10</td>
<td>8.9</td>
<td>8–9.75</td>
<td>8–9</td>
<td>100%</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>26. Nonlinear characteristics</td>
<td>5.91</td>
<td>4.25–8</td>
<td>6.17</td>
<td>5–8</td>
<td>5–8</td>
<td>61%</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>
Figure B.4: Bar chart of average ratings for first half of the concepts from Delphi rounds 2-4 and the follow-up survey.
Figure B.5: Bar Chart of Average Ratings for Second Half of the Concepts From Delphi Rounds 2-4 and the Follow-up Survey
Figure B.6: Scatter Plot of Average Ratings for Each Concept From Delphi Round 4 vs. the Follow-up Survey
### B.6.3 Laboratory components

Table B.4: Additional statistics for laboratory component items.

<table>
<thead>
<tr>
<th>Item</th>
<th>Round 2</th>
<th></th>
<th>Round 3</th>
<th></th>
<th>Round 4</th>
<th></th>
<th>Follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>IQR</td>
<td>M</td>
<td>IQR</td>
<td>IQR</td>
<td>%</td>
<td>Rank</td>
</tr>
<tr>
<td>1. LabVIEW</td>
<td>4.41</td>
<td>2–7</td>
<td>4.13</td>
<td>2–5.75</td>
<td>2–6</td>
<td>39%</td>
<td>12</td>
</tr>
<tr>
<td>2. Mathworks Software</td>
<td>8.41</td>
<td>8–10</td>
<td>8.67</td>
<td>8–9.75</td>
<td>8–9</td>
<td>97%</td>
<td>1</td>
</tr>
<tr>
<td>3. Programming languages</td>
<td>4.44</td>
<td>2–6.75</td>
<td>4</td>
<td>2–5</td>
<td>2–5</td>
<td>58%</td>
<td>13</td>
</tr>
<tr>
<td>4. Microcontrollers</td>
<td>5.91</td>
<td>3.25–8</td>
<td>5.4</td>
<td>3.25–7</td>
<td>4–7</td>
<td>52%</td>
<td>9</td>
</tr>
<tr>
<td>5. Programmable logic controllers (PLCs)</td>
<td>4.15</td>
<td>1.25–6</td>
<td>3.4</td>
<td>2–5</td>
<td>2–4.25</td>
<td>65%</td>
<td>15</td>
</tr>
<tr>
<td>6. Electro-Mechanical systems</td>
<td>8</td>
<td>7–10</td>
<td>8.57</td>
<td>8–9</td>
<td>8–9</td>
<td>84%</td>
<td>2</td>
</tr>
<tr>
<td>7. Mechanical systems</td>
<td>7.26</td>
<td>6–9</td>
<td>8</td>
<td>8–9</td>
<td>7–9</td>
<td>77%</td>
<td>3</td>
</tr>
<tr>
<td>8. Electrical systems</td>
<td>7.06</td>
<td>6–8</td>
<td>7.3</td>
<td>7–8</td>
<td>7–8</td>
<td>84%</td>
<td>5</td>
</tr>
<tr>
<td>9. Fluid or thermal systems</td>
<td>5.41</td>
<td>3.25–7.75</td>
<td>5.5</td>
<td>4–7</td>
<td>5–6</td>
<td>71%</td>
<td>10</td>
</tr>
<tr>
<td>10. Physical lab bench equipment</td>
<td>6.09</td>
<td>4.25–8</td>
<td>6.4</td>
<td>5–8</td>
<td>6–8</td>
<td>61%</td>
<td>14</td>
</tr>
<tr>
<td>11. Virtual or simulated lab bench equipment</td>
<td>4.59</td>
<td>2–6</td>
<td>4.27</td>
<td>2.25–5</td>
<td>3.75–5</td>
<td>68%</td>
<td>11</td>
</tr>
<tr>
<td>12. Data acquisition</td>
<td>6.65</td>
<td>5–9</td>
<td>7</td>
<td>6–8</td>
<td>7–8</td>
<td>71%</td>
<td>6</td>
</tr>
<tr>
<td>13. Tools representative of industry</td>
<td>7.03</td>
<td>6–8</td>
<td>7.5</td>
<td>7–8</td>
<td>7–8</td>
<td>94%</td>
<td>4</td>
</tr>
<tr>
<td>14. Digital and analog I/O</td>
<td>6.21</td>
<td>4.25–8</td>
<td>6.8</td>
<td>6–8</td>
<td>7–8</td>
<td>94%</td>
<td>7</td>
</tr>
<tr>
<td>15. A/D and D/A conversion</td>
<td>5.91</td>
<td>3.25–8</td>
<td>6.27</td>
<td>5.25–7</td>
<td>6–7.25</td>
<td>77%</td>
<td>8</td>
</tr>
</tbody>
</table>
Figure B.7: Bar chart of average ratings for each component from Delphi rounds 2-4 and the follow-up survey.
Figure B.8: Scatter plot of average ratings for each laboratory component from Delphi round 4 vs. the follow-up survey.
APPENDIX C

PROJECT MANAGER INTERVIEW PROTOCOL

C.1 Interview questions

1. What is your major?

2. What was your standing at the university at the time you were a [PEC] Project Manager (PM)? Junior? Senior? Graduate student?

3. What is your gender?

4. Are you a domestic or international student?

5. What are your career goals?

6. Why did you become a [PEC] PM?

7. During the APM class we talked about the knowledge, skills, and values, attitudes, and dispositions we gained during our experience. What were the three most important things in any of those categories that you learned as a PM?

8. What do you wished you would have done differently as a [PEC] PM?

9. Which project management knowledge areas did you learn as a [PEC] PM?*

10. Did you learn any other project management knowledge not covered on this list?

11. Can you provide a specific example of how you applied one of these project management knowledge areas as a [PEC] PM?

12. What interpersonal skills did you practice as a [PEC] PM?*

13. Did you apply any other interpersonal skills not on the list?
14. Can you provide a specific example of how you applied one of these interpersonal skills as a [PEC] PM?

15. What process groups did you experience as a [PEC] PM?*

16. Did you apply any other processes not on the list?

17. Can you provide a specific example of how you applied one of these process groups as a [PEC] PM?

18. If your [PEC] experience prepared you for the project management certification exam, would you be interested in becoming a Certified Associate in Project Management through the Project Management Institute?

19. Looking back, is there anything you would change about the structure of [PEC]?

20. Did you have any prior experience that helped you succeed as a [PEC] PM?

*Lists and brief definitions of the project management knowledge areas, interpersonal skills, and process groups will be provided with these questions. These tables are included in the next section.

C.2 PMBOK skill tables use in interviews

Each table was adapted from the PMBOK (PMI, 2013).
Table C.1: Interview table for project management knowledge areas (1 of 4).

<table>
<thead>
<tr>
<th>Knowledge Area</th>
<th>Description</th>
<th>Experienced as a PM</th>
<th>Learned in APM</th>
<th>Not Covered / Do Not Remember</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Integration Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Develop project charter</td>
<td>Document the project and authorize resources for the project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Develop project management plan</td>
<td>Document how the project will be executed, monitored, and controlled. It also includes the initial scope and budget for the project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct and manage project work</td>
<td>Leading and completing project work, implementing changes as needed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitor and control project work</td>
<td>Tracking and reporting project progress</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perform integrated change control</td>
<td>Review and process all change requests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Close project or phase</td>
<td>Finishing all activities to complete the project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Project Scope Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan scope management</td>
<td>Define how project scope will be defined, validated, and controlled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collect requirements</td>
<td>Document stakeholder requirements to meet project objectives</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Define scope</td>
<td>Create a detailed description of the project/product</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Create WBS</td>
<td>Subdivide deliverables and other work in to manageable pieces</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Validate Scope</td>
<td>Confirming acceptance of completed project deliverables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control Scope</td>
<td>Manage changes to the scope baseline</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table C.2: Interview table for project management knowledge areas (2 of 4).

<table>
<thead>
<tr>
<th>Knowledge Area</th>
<th>Description</th>
<th>Experienced as a PM</th>
<th>Learned in APM</th>
<th>Not Covered / Do Not Remember</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Time Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan schedule management</td>
<td>Document how to plan and manage the project schedule</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Define activities</td>
<td>Document specific activities to produce the project deliverables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sequence activities</td>
<td>Document the relationships between activities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimate activity resources</td>
<td>Estimate the resources (e.g., money, people, equipment, material) required to complete an activity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimate activity durations</td>
<td>Estimate the time to complete an activity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Develop schedule</td>
<td>Create a schedule based on the sequence, resources, and durations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control schedule</td>
<td>Monitoring the project schedule</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Project Cost Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan cost management</td>
<td>Document the plan for managing and controlling costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimate costs</td>
<td>Approximate the cost of the resources needed to complete the project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Determine budget</td>
<td>Create a budget and cost baseline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control costs</td>
<td>Monitor the status of the project costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Project Quality Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan quality management</td>
<td>Identify quality requirements and create a process for quality compliance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perform quality assurance</td>
<td>Audit the quality requirements and quality control measurements to ensure standards are being met</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control quality</td>
<td>Monitor and record the quality activities</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table C.3: Interview table for project management knowledge areas (3 of 4).

<table>
<thead>
<tr>
<th>Knowledge Area</th>
<th>Description</th>
<th>Experienced as a PM</th>
<th>Learned in APM</th>
<th>Not Covered / Do Not Remember</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Human Resource Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan human resource management</td>
<td>Document project roles and responsibilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acquire project team</td>
<td>Build the team necessary to complete the project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Develop project team</td>
<td>Improve members of the team and the interaction between team members</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manage project team</td>
<td>Track team member performance and provide feedback</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Project Communications Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan communications management</td>
<td>Document communications based on stakeholder’s information needs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manage communications</td>
<td>Collect and distribute information per plan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control communications</td>
<td>Monitor communications on the project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Project Risk Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan risk management</td>
<td>Document the process for risk management</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identify risks</td>
<td>Identify risks that may affect the project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perform qualitative risk analysis</td>
<td>Prioritize risks for further action</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perform quantitative risk analysis</td>
<td>Numeric analysis of the impact of a risk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan risk responses</td>
<td>Develop options or actions to reduce risks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control risks</td>
<td>Track risks and implement risk response plans</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table C.4: Interview table for project management knowledge areas (4 of 4).

<table>
<thead>
<tr>
<th>Knowledge Area</th>
<th>Description</th>
<th>Experienced as a PM</th>
<th>Learned in APM</th>
<th>Not Covered / Do Not Remember</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Procurement Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan procurements</td>
<td>Document procurement decisions and approach for finding suppliers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conduct procurements</td>
<td>Identify, compare, and determine suppliers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control procurements</td>
<td>Manage supplier relationships and monitor contract performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Close procurements</td>
<td>Complete each procurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Project Stakeholder Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identify stakeholders</td>
<td>Determine people or organizations that could be impacted by activities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plan stakeholder management</td>
<td>Document a process for engaging stakeholders throughout the project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manage stakeholder engagement</td>
<td>Work with stakeholders to meet their expectations and address issues</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control stakeholder engagement</td>
<td>Monitor stakeholder relationships</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

169
Table C.5: Interview table for interpersonal skills.

<table>
<thead>
<tr>
<th>Interpersonal Skill</th>
<th>Description</th>
<th>Experienced as a PM</th>
<th>Learned in APM</th>
<th>Not Covered / Do Not Remember</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leadership</td>
<td>Focus a team on achieving project goals through respect and trust</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Team building</td>
<td>Use activities to bring the team together and align with the goals throughout the duration of the project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motivation</td>
<td>Create an environment maximize the satisfaction of team members and meet project goals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td>Employ open and effective communication with the team and all stakeholders (e.g., adapting your communication style, active listening)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Influencing</td>
<td>Apply your skills and position to get the team to work toward common goals (e.g., transparency, leading by example)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decision making</td>
<td>Use a decision making process to define, act, and review decisions that will impact the team or project’s success</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Political and cultural awareness</td>
<td>Navigate organizational politics and capitalize on cultural differences to meet project goals</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Negotiation</td>
<td>Conferring with key parties to move toward a compromise or agreement to move forward</td>
<td></td>
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</tr>
<tr>
<td>Trust building</td>
<td>Use cooperation, transparency, and effective problem resolution to build and maintain trust with the team and other stakeholders</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conflict management</td>
<td>Identify potential causes for conflict and actively manage the conflict to minimize the negative impact to the team</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coaching</td>
<td>Aid team members in developing skills necessary to enable project success</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table C.6: Interview table for process groups.

<table>
<thead>
<tr>
<th>Process Group</th>
<th>Description</th>
<th>Experienced as a PM</th>
<th>Learned in APM</th>
<th>Not Covered / Do Not Remember</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiating</td>
<td>Processes performed during the definition of a project: define scope and budget; identify stakeholders; and form team. All of this information is captured in a Project Charter</td>
<td></td>
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</tr>
<tr>
<td>Planning</td>
<td>Define project objectives and determine a plan to complete the objectives. The project management plan includes documentation of scope, schedule, budget, quality, communications, risks, etc.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Executing</td>
<td>Completing the work of to achieve the projects objectives. This includes project execution and managing stakeholder expectations.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Monitoring and controlling</td>
<td>Track progress on the project and manage changes to the scope and schedule at regular intervals.</td>
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<td></td>
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</tr>
<tr>
<td>Closing</td>
<td>Send deliverables to the customer and obtain approval; complete a post-project review and document lessons learned; archive relevant materials; perform team member assessment; and complete procurement activities.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>