A Revised Undergraduate Controls Lab Featuring Exposure-Based Experiences

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1 Introduction

Most ABET accredited undergraduate mechanical engineering programs have some sort of controls course and accompanying laboratory experience [1]. The goal of most of these laboratory courses is to give the students hands-on experience working with hardware and implementing control algorithms while learning the theory in an accompanying lecture course. As early as 1981, Balchen et al. [2] asserted that the criteria for a good experiment is that it should (1) demonstrate important theoretical ideas, (2) reflect important real-life problems, (3) give visual and acoustic sensation, (4) have a suitable timescale, (5) be nonhazardous, (6) be inexpensive, and (7) be easy to understand and use. With today's technological advances, designing a laboratory course that addresses all of these constraints is more feasible than ever. However, many existing laboratory courses and off the shelf modules violate one or more of these constraints, and therefore fail to deliver an optimal lab experience.

There are two opposing routes to take when designing an undergraduate controls laboratory: use commercial off the shelf (COTS) hardware and accompanying software, or design the hardware and use or design open source software. There are many advantages to following the first route: efficient use of course preparation time, well-tested hardware and software is less error prone, variety in available modules, etc.. Popular hardware suppliers for such undergraduate controls laboratories include Educational Control Products, Quanser, Googol Technology, and dSpace. While the hardware is excellent and curriculum exists for all provided modules, they fail to address some of the constraints mentioned above. Few of the supplied modules (e.g., inverted pendulum [3]) reflect important real-life problems. The software that ships with Educational Control Products hardware is proprietary and only works with their hardware, although an optional extension that works with MATLAB (The Mathworks, Inc,) is available. Similarly, the Quanser hardware is controlled through proprietary add-on software with QUARC for MATLAB/Simulink or QRCP for LabVIEW (National Instruments), Googol's products are controlled through MATLAB, and dSpace uses its own software to generate and then download code specific to dSpace boards. At several thousand dollars per station for even the simplest modules, and more for the software, these systems are an expensive way to build a lab.

The second route that some universities take when developing their controls labs is a more do it yourself (DIY) approach [4]–[6]. This has several advantage over the fully COTS approach, e.g., custom designs may better reflect real world problems, and the combination of custom hardware and open source software can be significantly less expensive. Popular hardware providers for this route include Arduino, Sparkfun, and Adafruit, with software from Arduino and Python. All of the products that these three companies manufacture are open source hardware, and Arduino and Python are open source software that power much of the hardware. Furthermore, there is some evidence that use of instructor designed laboratory experiments correlates to an increased understanding of and interest in the material [7].

When we redesigned our undergraduate controls course, our goal was to enhance our inventory of realistic hardware and software systems while focusing on exposure to different hardware and software that students would potentially encounter should they choose to pursue controls engineering in their careers. This exposure-based approach is different from the accounts of most controls laboratories we found in literature, and often ends up being a practical hybrid between the fully COTS and fully DIY approaches described above. This paper is presented as a case study that describes our approach to redesigning our 1 credit, junior level, Vibrations and Controls Laboratory course that 120-150 mechanical engineering students are required to take each Fall semester. Preliminary data on the effectiveness of the redesign is presented. The end goal is to provide a template for other universities to follow to achieve similarly positive outcomes in terms of student engagement.

2 Criteria for a Successful Laboratory Course

Although Balchen et al. [2] came up with an initial set of criteria, they are incomplete and were not well supported by the literature available at the time. In the three decades since the publication, it goes without saying that the availability and affordability of enabling technology are quite different today than they were then. Additionally, advances in engineering education and pedagogy have been made that deserve inclusion. In order to update these criteria, the authors offer the following adjustments with support from the literature. Each heading follows from the prompt “a good experiment should…”.

2.1 Demonstrate important theoretical ideas

There is a lot of theoretical presentation of control theory in traditional classrooms. Experiments should demonstrate practical applications of theory [8]–[11].

2.2 Reflect problems and situation students may encounter in real life

Students should be trained on hardware and software that reflects what they might use or see in real life so they know when to apply what they have learned to systems they might encounter [8], [12]. The topics of the experiments should not only have practical uses, the students should be aware of these uses [13].

2.3 Be enjoyable, interactive, and promote active learning

Bencomo and others [4], [14] assert that interactivity is critical in laboratory settings. Interactivity in this context means that students must be able to see changes in a system’s behavior based on their adjustments. In the case of a control systems experiment, this means that it must be obvious to students that improvements to the controller design lead to observable system performance improvements. Taylor et al. [4] went as far as to say that for a control systems experiment, the system should be open-loop unstable so that is was too difficult to control using ad hoc open-loop methods, therefore requiring students to apply the control theory they had learned. Interactivity helps reinforce criteria 1 because students will realize the physical consequences of the abstract or general theory they have learned. Interactivity also helps reinforce criteria 2, since students will gain intuition pertaining to handling similar situations in real life.

We know that enjoyment of a task increases its perceived value to students [15], and thus heightens engagement and learning [16]. Experiments should therefore be tuned to their specific audience, such that the lab becomes an enjoyable experience instead of merely a hoop needing to be jumped through to progress.

2.4 Appeal to different types of learning styles

Balchen et al. [2] said that experiments should “give visual and acoustic sensation”.
namely Visual, Auditory, Read/Write, and Kinesthetic (VARK) modalities [17].

2.5 Provide a reasonable return on investment (ROI)

It is not enough to say that an experiment should be low cost, because low is relative to the institution. Additionally, a low cost experiment that needs repurchase every year or two is not necessarily lower cost than specialty hardware that is purchased once then lasts 20 years. Low cost is certainly a component of getting a good ROI [2], [4], but it is not the whole story.
If the cost can be brought down enough for a particular institution to purchase more units, the potential for individual or even portable lab equipment emerges [4]. So, a reasonable ROI could range from a high initial cost for hardware and software that will last for 20 years, or for cheaper hardware that could be considered disposable such that restock cost is negligible.

2.6 Be open and open-ended

Feedback on courses employing more practical, open source hardware (e.g., Arduino) has been superior to feedback received using specialty hardware [18]. The use of open source hardware and software tends to bring down the cost of experimentation.

Open-ended lab formats, where the students are given some baseline instruction but then work independently to solve a problem, have been shown to increase the perceived value of a course [4]. Further, such open-ended experiments enable problem-based learning [19], which is shown to be an effective method for gaining problem solving skills and learning in such a way that acquired knowledge can be utilized flexibly [20].

2.7 Be physically and logically robust

The equipment needs to be sufficiently designed to withstand general mistreatment on the part of the student [4]. Robust hardware will have a better return on investment because it will see many years of use before needing replacement. Aside from hardware failures, it’s also frustrating to students when something in the implementation of an experiment doesn’t go as planned, and there is no obvious logical reason [13]. The hardware, software, and implementation procedure all need to be robust enough that when things inevitable do go wrong, there is an obvious logical reason, and instructors can work with students to get them past such setbacks. This is one area where the COTS systems shine.

2.8 Safety

The level of safety required is relative to the number of support staff available to administer a given experiment. In the extreme case of portable or take-home labs, the experiments must be safe for unsupervised use [4].

2.9 Exposure

From the perspective of industry, exposure to multiple control systems is more useful than a slightly more in-depth look at a single one [8]. This is also supported by data from our alumni survey below.

Exposure to proprietary software like LabVIEW and MATLAB is important since these tools are often used in industry for virtual instrumentation. However, the use of proprietary add-ons and layers that sit atop these pieces of software can obscure some of the features used more pervasively in industry. And while these programs contain libraries, toolboxes, and other elements that can make implementing a controller more efficient, exposure to the details of implementation is more important than efficiency at the level of an introductory lab course.

Many industrial control solutions use ladder logic through Programmable Logic Controllers (PLCs) [21]. The use of PLCs in controls lab corresponds to a better understanding and comfort with using practical modern technology, and makes students more confident in their abilities to solve controls problems. Other educators have found that students were easily able to explore the capabilities of the PLC platform with very little external input [22].

3 Overview of the Laboratory Course and Experiments

The course breaks the enrolled students into teams of 3-4 students, which do not change during the semester. With four lab stations available, and three distinct 1 hour 45 minute long lab sections offered throughout the week, we were restricted to three week spacing between each lab, which amounted to four labs for the entire semester. For each of the labs, students are to prepare formal reports individually, addressing the key topics covered by the experiment. Within their teams, mandatory peer review and evaluation assignments were given for each experiment to improve the quality of final submissions.

The first experiment in the course served to emphasize the portion of the lecture focused on vibrational motion.An ECP Model 210 Rectilinear Plant presented a pseudo-ideal mass-spring-damper system with which to verify mathematical concepts presented during lecture. Students were instructed to program the plant with pre-set parameters using the ECP proprietary software. Then, they were to analyze the acquired data using analytical and graphical methods and demonstrate agreement with the mathematical model. This experiment was a combination of those from the original course design, and was implemented to serve as a sort of control relative to the three other completely new experiments. The cost for this experiment is $14,950 per station for the Rectilinear Plant and required peripherals.

The second experiment utilized a National Instruments myDAQ and the Pitsco Education myVTOL – a 1 DOF assembly designed to allow students to experiment with thrust management in a vertical take-off and landing scenario. The purpose of this lab was to allow students to understand the tasks performed by a conventional PID controller, and gain an appreciation for the function of each gain as well as the inner workings of a controller implementation while providing exposure to National Instruments LabVIEW. The complete hardware system used can be seen in Figure 1. Three custom LabVIEW Virtual Instruments (VI) were designed for the exercise, and the students interacted with each to learn about different aspects of the control system. The first VI allowed students manual control of the myVTOL's fan speed and prompted them to keep the fan's height within an acceptable range that could be held constant or varied in a sinusoidal fashion. The second VI provided a pre-programmed PID algorithm that allowed students to observe the system behaving in an optimal fashion with optimized PID gains. Then, students were directed to vary each of the gains independently, then in tandem, to visualize each gain's effect on the system's behavior. Finally, students were to tune the system's gains themselves to meet settling time and overshoot constraints. The optimized gains were not made visible to students to avoid providing any prior notion as to what any given gain should be. The third and final VI provided a shell in which students built their own PID algorithm within LabVIEW based off a provided block diagram. The shell provided all the I/O functionality, as well as shift registers to handle recursion such that the students would be able to work through the problem without any prior LabVIEW programming experience after a brief tutorial on the LabVIEW environment. It also included ways to probe the contribution of various terms to pinpoint any errors they might have. Students were given liberties over their implementations, and could build in any optimizations or improvements they saw fit until they were satisfied with its function. The hardware cost for this experiment is approximately $350 per station.

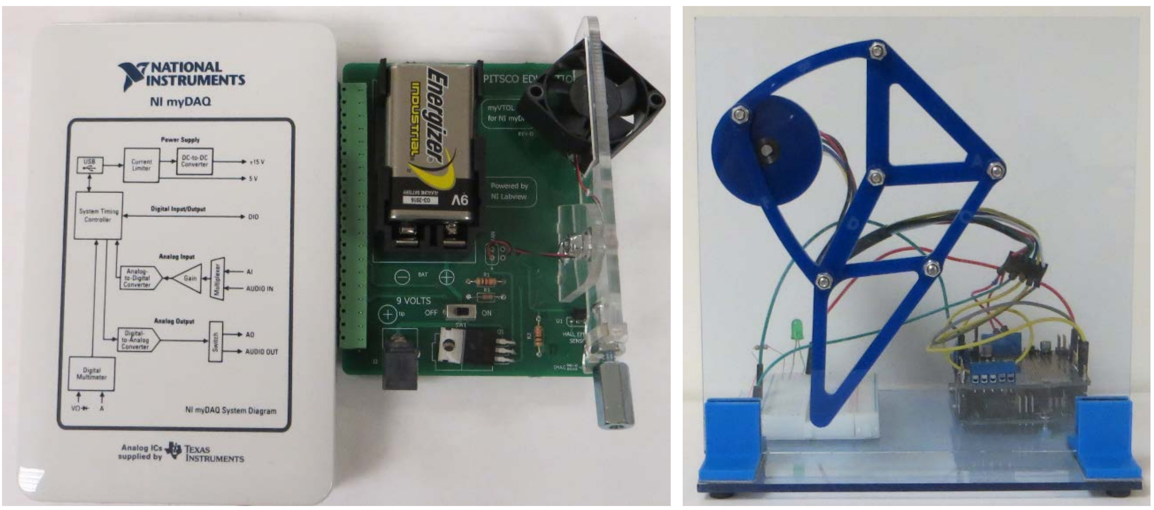

Figure 1: (Left) myDAQ & myVTOL from Lab 2, (Right) Theotbot from Lab 3

The third experiment of the course used an Arduino Uno in tandem with an Adafruit Motor Shield to regulate the movement of an internally designed and produced motor driven mechanism pictured in Figure 1. This is a playful variation on the classic experiment in DC motor control that is popular in control systems labs [6], [23] that provides exposure to Arduino microcontrollers commonly used in prototyping. To simulate the steps involved in system identification, students were provided the full transfer function for the system and asked to analyze it using MATLAB. They were to first contemplate the possibility of order reduction, and establish which pole was dominant. This was followed by calculation of possible gains and stability conditions for both a P and PI controller, given specifications for percent overshoot and steady-state error. Using appropriate gains and a pre-programmed algorithm in Arduino (a user-friendly implementation of C++), students implemented their controller in hardware. Students were then directed to implement a state indicator that described the current position of the mechanism, since most industrial control solutions require systems to indicate their status. Finally, students collected data from the system as it operated and compared their results with the provided specifications, and explain any problems that may or may not have inhibited their system from meeting the prescribed specifications. The total hardware cost for this lab is about $80 per station, with the parts for the leg and base made on in-house laser cutting and 3d-printing devices.

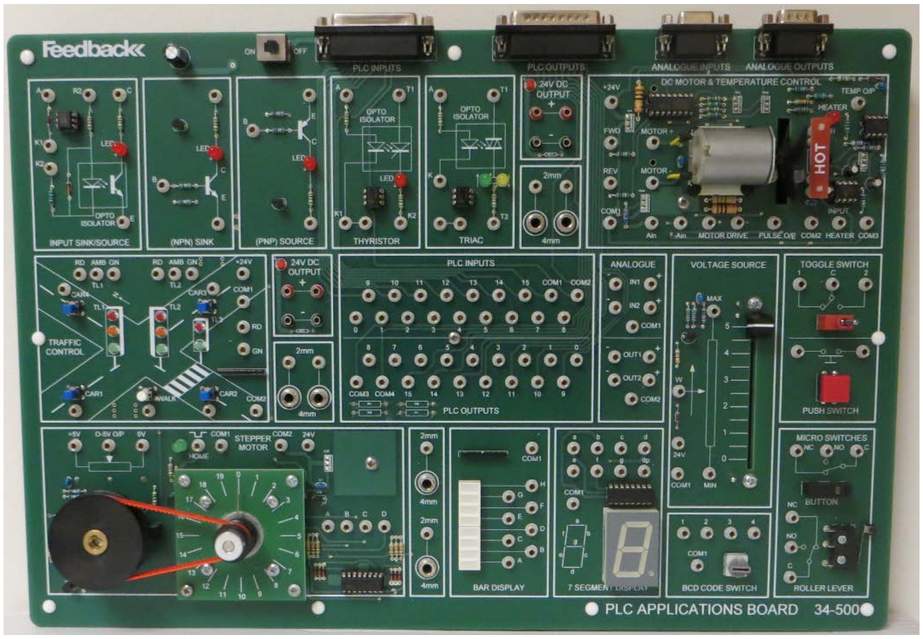

Figure 2: PLC Trainer Board for Lab 4

The final experiment employed an industry standard Siemens S7-1200 PLC in conjunction with a PLC Training Board from Feedback Instruments (Model 34-500, Figure 2) to cover bang-bang control paradigms while providing experience with the industry-pervasive ladder logic programming language. Students were first asked to wire their trainer independently of the controller to simulate an emergency-off situation. Then, students were presented with increasingly complex configurations for the trainer board and asked to program the controller to have the system behave as described by pre-determined specifications. These scenarios ranged from implementing discreet on and off buttons to a scenario where a timed run of a motor was triggered by a certain pattern of inputs. Variation in the patterns requires constant interactivity with the system, with each step expanding on previous patterns so there's a clear place to look for an error should one arise. This variation also allows the experiment to span a wide variety of scenarios analogous to small tasks existing in industry. Since students were expected to have no experience with ladder logic, each task was preceded by a quick tutorial of any new operators they would need. The final task presented to the students was to improve the function of a pre-programmed traffic light algorithm. The starting algorithm merely switched between green and red on a timer, students were expected to implement yellow lights as well as double-red states, and time permitting they were given the opportunity to integrate car presence sensors, a pedestrian crossing, and a mode in which a traffic officer could seize control of the indicator and advance the states manually. Although even a complicated traffic light system is not nearly as complex as most real world control systems, the experiment is kept intentionally simple since this is the first (and only) time in the undergraduate curriculum that students are exposed to PLCs or ladder logic. The cost of all materials needed for a single station for this lab was approximately $2,200.

A self-evaluation was performed to determine what experiments adhered to the criteria we developed for ourselves (Table 1). As expected, the three newly developed labs addressed the majority of the criteria intended, but the lab recycled from previous years did not.

Table 1: Matrix evaluating labs used in the controls course based on the criteria described in Section 2.

	2.1 Demonstration of Ideas	2.2 Considers Real Life Problems	2.3 Enjoyable & Interactive	2.4 Appeal to Learning Styles	2.5 Good Return on Investment	2.6 Open and/or open-ended	2.7 Physical and Logical Robustness	2.8 Safety	2.9 Exposure to Control Systems
Lab 1	✓			✓			✓	✓	
Lab 2	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lab 3	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lab 4	✓	✓	✓	✓	✓	✓	✓	✓	✓

4 Impact on Students

Two surveys were conducted to measure and document the impact on students. The first survey was a subset of a larger survey sent to all alumni of the department of mechanical engineering with active email address (2,301 total) and was active for a two-week period spanning September and October 2015. Despite the relatively low number of responses (141, or 6%), there were still enough data to support the inclusion of several of our above criteria.

The second was sent to current juniors and seniors within a month of completing the first semester of the redesigned course, and was designed to see if they felt that the newer experiments would be more relevant to their future coursework and employment. The second survey was available for one week, and had a response rate of 39% (38 out of 97). In addition to surveys, standard anonymous course evaluations solicited feedback from students in several areas.

4.1 Survey Results

Results from the first survey indicated that previously, there was a need for improvement within the laboratory curriculum. While 69% of respondents agreed that lab exercises rated either as "Very Effective" or as "Effective" for active learning, the average rating for "the overall quality and frequency of active learning" in laboratory courses was only 2.4 on a scale of 0 to 4. 51% of respondents asserted that the frequency of active learning in lab classes should be increased. In response to what topics they felt exposure to was valuable in a mechanical engineering curriculum, 73% responded with advanced analytical software (e.g. MATLAB), 71% with computer control & data acquisition, 51% with integrated PLC control, and 47% with microprocessors.

The second survey prompted participants to rank the labs they had participated in on the criteria of how well each prepared them to utilize a controls solution in a real world application (2.2), how effectively each made use of time for learning, the degree to which each challenged students to think critically and explore interests, and finally how enjoyable each task was (2.3). Across all prompts, Lab 1 (the COTS lab utilizing the rectilinear plant) ranked worst by a large margin, Lab 4 (the PLC experiment) ranked best, and Lab 3 (the Arduino Theobot) and Lab 2 (VTOL with LabVIEW) shared the middle spots (Figure 3).

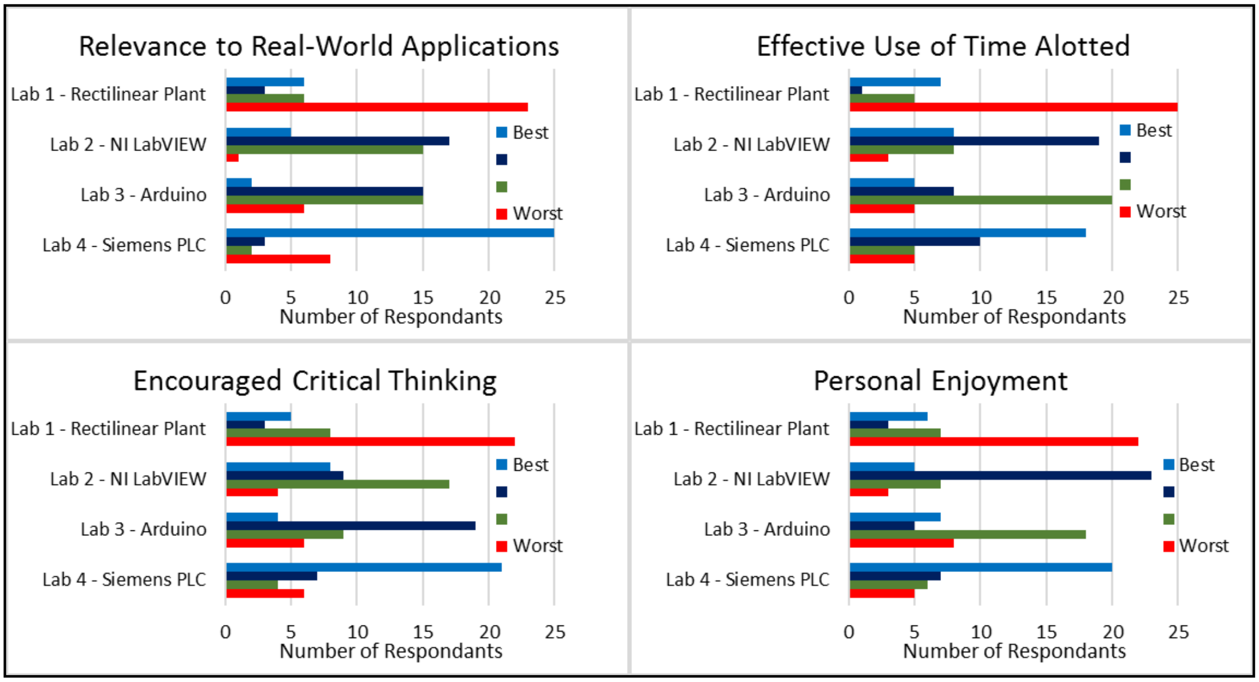

Figure 3: Results of the second survey. Respondents rated revised labs above a fully COTS lab in all categories

Feedback from the university's course evaluation was generally positive. The following three quotes from the free-response questions support the labs that address the majority of the criteria determined above: (1) "I liked how it turned the conceptual topics we learned in class into real physical experiments. It helped me get a better understanding of why certain concepts were really relevant in the real world." (2) "Labs were cool and interesting. Introductions to LabVIEW, PLC software, etc. was useful." (3) "Enjoyed working on the different equipment in the lab."

The students also had relevant criticisms that supported our assumptions about the first lab. Comments included "The only thing I would try to change or revise was the length and tediousness of Lab #1." and "First lab was a bit boring compared to the controls labs." Most other criticisms focused on synchronization with the lecture component and a preference for group reports instead of the individual reports required of them.

5 Conclusions and Future Work

Overall, we are satisfied with the improvements made during the modified course's first offering. Formally and informally solicited student feedback indicates that the modified course addresses criteria it previously did not cover. The revised course also better aligns itself well with the needs of our graduates. However, this course redesign is still a work in progress, and there are weaknesses in each lab that we intend to address in the next iteration.

The clear first step is the replacement of the first experiment. As it currently exists, it is the least compatible with our criteria and does little to achieve the course goals. Its replacement will still need to cover vibrations and open-loop control, but will do so in alignment with the developed criteria. The most likely path forward here is to use the same hardware, but upgrade the software so students can use MATLAB or LabVIEW instead of the proprietary software that ships with the hardware. In doing so, procedural changes can be implemented to enrich the learning experience.

In lab 3, the weak points in the procedure were giving them the transfer function instead of having them determine it, and then integrating an LED indicator. The authors plan to investigate a way to allow system identification to happen during the lab period, which will require streamlining the process and directions to be easier to follow. Additionally, the LED indicator section will be written in a way that students have to struggle a bit to implement, which will help refine their debugging skills.

Another intended change involves the ordering of the labs. A common student criticism was that depending on which section a student participated in, there could be a discrepancy between what topics the lecture had covered and the concepts covered by the experiment. Moving the fourth lab earlier in the course should alleviate this issue, as a minimal amount of background knowledge is required to perform exercises in bang-bang control.

Given these and other minor changes, the revised course should continue to reap the benefits of using industrially relevant hardware and software. Given our experience with the first offering and feedback received, the change means our department is taking steps in the right direction to better prepare our graduates for their future careers. Other than lab content and organizational changes, the survey as an assessment tool will be refined. The next class to take this lab will evaluate each lab against the criteria in section 2 directly in their course evaluation, which should give us a significantly higher response rate and more confidence in our self-assessment of the labs in Table 1.

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