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# Incorporating Design in Electronics Laboratories

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## Introduction and background:

Engineering courses often comprise a laboratory section but there is little consensus about the learning objectives of the laboratories and the best didactic approaches to adopt to reach these objectives [1]. Desirable learning objectives include developing the students ability to design a system to satisfy requirements and demonstrating independent thought and creativity in real-world problem solving [1]. Yet, out of tradition, or to propose experiments that work in the hands of most students, instructors often use laboratory assignments that are essentially of the "cook-book" type with well-defined experiments, pre-determined setups and instruments to use for the measurements, and predictable results which can be obtained by simply applying the theory discussed in class. "Cook-book" approaches to laboratory experimentation in the sciences have been shown to produce no learning benefits and fail to help students develop creativity or an increased interest for the field [2]. Alternative formats to the "cook-book" laboratories have been proposed which emphasize guided inquiry. In this format, students work in groups to ask questions, propose experiments to address these questions and perform multi-week experimental investigations [2]. Open-ended experiments in environmental engineering laboratories were found to improve the students' understanding of subject matter concepts and their ability to design and conduct experiments [3]. Inquiry-based laboratory experiments were applied to a mechanical engineering course by asking students questions to answer through the experiments, requiring them to plan experiments to obtain the data necessary to answer their questions, perform the experiments they had planned and explain their results in relation to theoretical considerations and measurement errors [4]. Surveyed students found that the inquiry-based laboratory experiments provided a sufficiently challenging learning experience which they preferred to the traditional "cook-book" laboratories. In this context, we describe the implementation of design-focused laboratories in a medical electronics course and the students feedback gathered at the completion of the course.

## Methods:

Design-focused laboratories were implemented in the "Medical Electronics" course offered at our institution to undergraduate students in Biomedical Engineering. The semester-long course is required for all students pursuing the BS degree in Biomedical Engineering, and has an enrollment of about 40 students divided between juniors and seniors. The course exposes students to fundamental analog electronic components and circuits found in most biomedical instruments, including medical transducers, pn and Zener diodes, operational amplifiers, instrumentation amplifiers, bipolar junction transistors, voltage dividers, and Wheatstone bridges. Applications of these components and circuits to common electronic functions, including sensing, amplification, filtering, dc power generation, and electronic switches are concurrently studied. Students attend two 80 min classroom sessions and one 3-hour laboratory every week. Two laboratories are held each week with approximately half of the enrolled students attending each laboratory. Prior to this course, all students took a standard "electrical circuits" course with laboratory.

The classroom sessions are organized in the "flipped classroom" format, with the learning material distributed through short narrated video presentations posted on the learning management system and supplemented with textbook readings. In the classroom, a short review of the content driven by students' questions is followed by group exercises in which the students work on problem sheets, with assistance from the instructor and the teaching assistant. With this format, the students are accustomed to preparing for class and learning the material in advance of the classroom activities.

The laboratory schedule (table 1) comprises four self-contained introductory laboratories in which students learn the use of the electronic test instruments available in the teaching laboratory (computer-based Virtualbench device, National Instruments) and of a circuit simulation software (Multisim v. 14, National Instruments). The students also practice with the format of the design-focused laboratories. In one laboratory, students investigate the measurement of the characteristic current-voltage curve of several types of pn-diodes and LEDs. A second laboratory is for students to design, implement, and test a linear DC power supply.

Thereafter, the students work on two multi-week projects: a 4-week project in which they design a dual-supply electrocardiogram (ECG) amplifier with microcontroller measurement of the cardiac activity and a second 4-week project in which they develop a single-supply electromyogram amplifier system coupled with actuation of light and sound indicators controlled by the intensity of the muscle activity.

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| Lab 1: Virtualbench instrumentation – electronic measurements – basic op-amp circuits |
| Lab 2: diode characteristics (students develop procedures) |
| Lab 3: Multisim circuit simulator – comparison between virtual and real circuits |
| Lab 4: Linear regulated power supply (students develop and validate design) |
| Project 1: Dual-supply ECG amplifier with heart beat counter and signal digitization |
| Part 1: Instrumentation pre-amplifier – baseline wandering suppression |
| Part 2: Gain amplifier - Peak detector – QRS detector |
| Part 3: Arduino programming – heart beat counter |
| Part 4: Arduino ECG sampling and transfer to computer |
| Project 2: Single-supply Electromyograph-controlled actuation |
| Part 1: single-supply instrumentation pre-amp – reference voltage |
| Part 2: Active high-pass and low-pass filters |
| Part 3: Gain amplifier – precision rectifier (absolute value circuit) |
| Part 4: Arduino EMG sampling – actuation: light + sound controlled by muscle activity |

Table 1: schedule of laboratories and projects

The preparation for the laboratories comprises a series of questions the students answer to develop a plan for the experimental procedures and for the measurements they will do in the laboratory (table 2). To devise answers to the questions, the students refer to the data sheets of the components they will use in the laboratory. The students also prepare schematics of the circuits they will implement and simulate the measurements they will carry out to verify that these measurements will provide answers to the questions of the assignments. Most important is that the students are not told what circuit to use or how to assemble it, what they should measure, or the range of voltages and currents they should use.

- How can you determine quantitatively the shape of the characteristic curve of a forward-biased diode?
- How do you construct a laboratory experiment that will allow you to make this determination and measure the characteristic curve? What will you vary? Over what range? What will you measure? What instruments will you use for your observations?
- What differences do you expect if you were to measure the characteristics of a small signal diode (1N914), a power rectifier diode (1N4001), a red LED, and a blue LED (for instance C503B-BCN-CVZ0461)? (You will need to study the data sheets for these devices to address this question.) What would you change in your experimental approach depending on the device you are studying?

Table 2: Sample questions for preparation of the diode characteristics laboratory

A similar approach is used for the multi-week projects, which are divided into weekly design tasks (table 1, figure 1). Working in pairs, the students prepare for the design assignment by reading through materials made for professional engineers including application notes and component data sheets. The students answer the preparatory questions provided in the assignment to select a circuit design, characteristics functional values (gains, critical frequencies) and matching component values (resistors, capacitors). The students also develop a circuit diagram with the circuit simulator and test the design to verify that the desired functional characteristics are achieved. When relevant, they also develop the microcontroller program to measure the relevant data and generate the correct control signals. The students summarize their preparatory investigations in a design report (one report per student pair) which is turned in before the lab such that the instructor and teaching assistants can identify misconceptions or design errors before the laboratory.

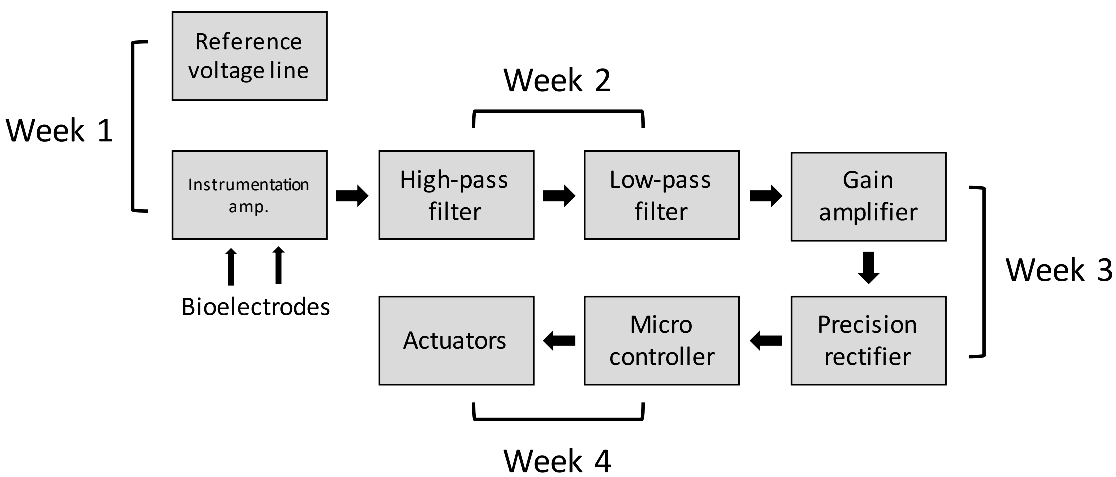


Figure 1: Block diagram of electromyography system with weekly design tasks that the students complete to design, implement and test for the second project.

On the day of the laboratory, we have a short (~30 min) discussion with the students to review how they addressed the preparatory questions and to discuss their circuit designs. Thereafter, the students work in pairs to develop and test their circuits while the instructor and teaching assistants work around the room to help the student pairs whose progress is slowed by wiring or measurement errors.

The students summarize their observations and data measurements in a report they complete each week after the laboratory session. We encourage them to reflect on what they learned by completing the laboratory and what they would improve if they had to do a similar design for a different goal.

Grading of the laboratory work emphasized the importance of the preparation and preliminary report (50% of laboratory grade) in comparison with the post-lab report (30%). Questions asked of the students at the end of each laboratory to check their involvement in the laboratory counted for 20% of the laboratory grade.

To assess the students response to the design-focused laboratory format, an anonymous survey was prepared using the Qualtrics software which was administered to the students in the last few weeks of the semester (table 3). The survey comprised 12 rating questions answered on a 1-5 Likert scale, 4 comment fields for free-response feedback, and two quantitative questions to evaluate the amount of time the students needed to complete the weekly preparation and post-laboratory report. The students answered the survey question on a voluntary basis. The response rate was 85%.

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| Rate the level of challenge of the laboratory experiments? |
| Prelab questions and readings help you prepare sufficiently for the labs? |
| Relying on professional documents enhanced the laboratory experience? |
| Was it helpful to use Multisim to design and test your circuits? |
| Did the Initial discussions help understand assignment? |
| Was it helpful to develop procedures with partner? |
| Were you sufficiently prepared by prior experience for this lab structure? |
| Did you gain sufficient experience to attempt other designs on your own? |
| Compare the approach of these laboratories to traditional "follow-the-steps" laboratories in terms of hands-on learning? |

Table 3: Principal survey questions used to assess the students' perceptions of the laboratories

**Results:**

Most student pairs successfully completed the laboratories and multi-week projects in the available time. The preparatory report grades initially decreased to a minimum of ~70% as the students adapted to the expectations of the preparatory report and gradually increased back to ~ 90% as the students became used to the laboratory format (figure 2).

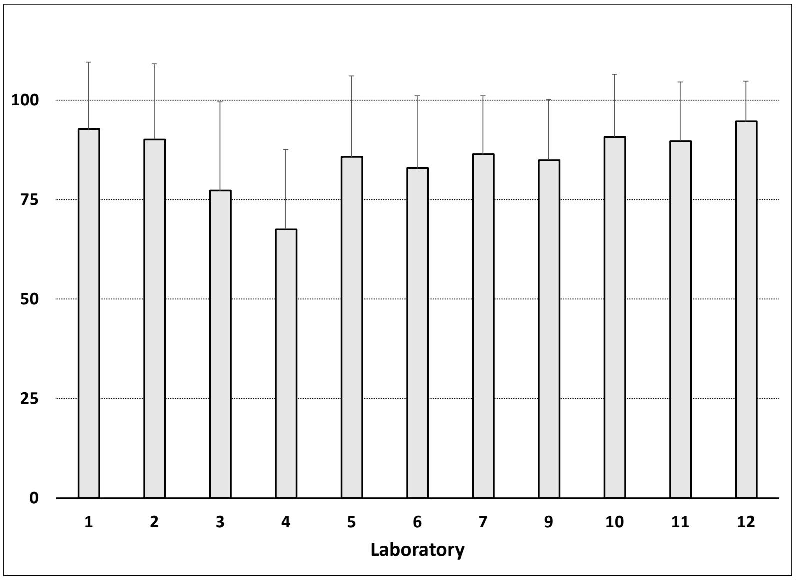


Figure 2: Mean grades for the preparatory reports. Error bars represent the standard deviations in all graphs (preparation for laboratory 8 was not graded).

Five survey questions addressed the level of challenge presented by the format of the design laboratories (figure 3). In general, the students found the format of the laboratories challenging and indicated that their previous laboratory experiences had only moderately prepared them for the design-focused format. The progression of the difficulty of the experiments was found to be adequate. The students reported spending on average 4.6 hours to prepare for the laboratory experiments and about 4 hours on the laboratory reports, with substantial variability among students.

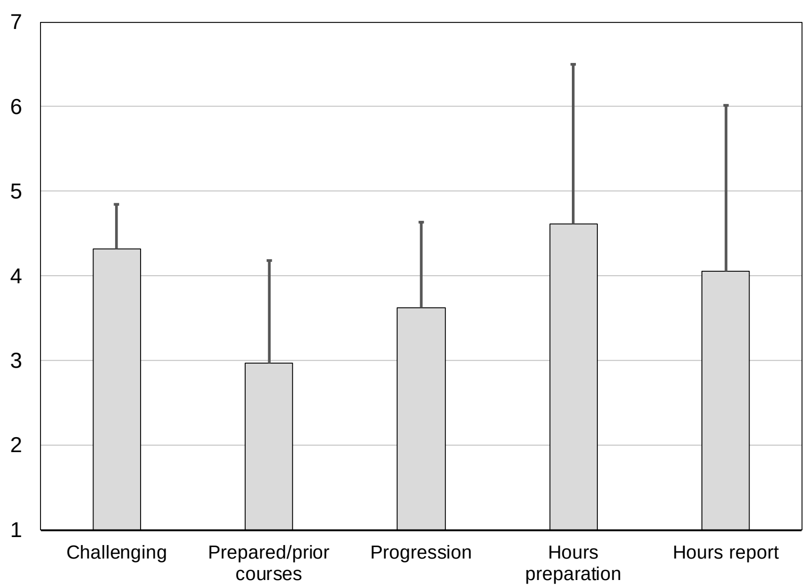


Figure 3: Survey responses related to the level of challenge of the laboratory format.

Four survey questions focused on the preparation for the laboratory experiments completed outside of class and at the beginning of the laboratory period (figure 4). Students found the readings and questions of the laboratory handout moderately helpful for preparing for the experimentations. They appreciated working on the preparation with a partner and found the initial group discussions beneficial even though the ideas presented by other students were judged to be of moderate usefulness.

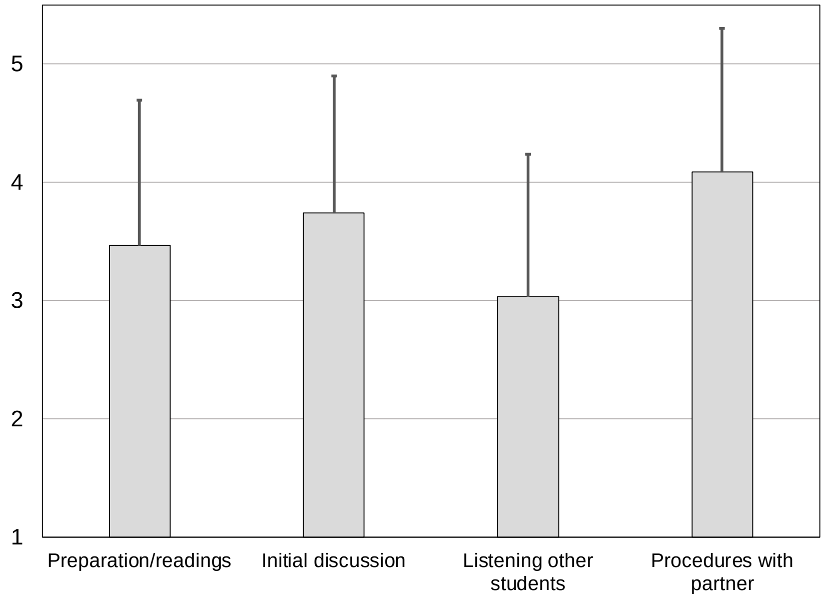


Figure 4: Survey responses related to the level of challenge of the laboratory format.

Using professional documentation to prepare for the labs was rated useful (4.1±0.8) as was the use of the circuit simulator (3.8±1.1). Overall, the students found the design-focused laboratories to be a beneficial learning experience, which was more useful than traditional laboratories in terms of hands-on learning (figure 5). They reported a moderate level of confidence in designing other electronic circuits on their own after these laboratories.

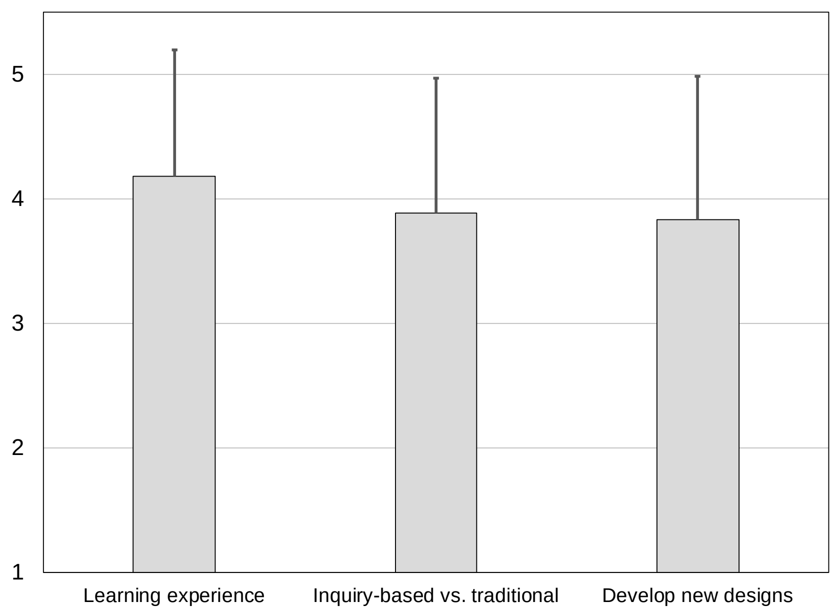


Figure 5: Survey responses related to the overall benefits of the design-focused laboratories

Free-hand comments indicated that the students found the laboratories very challenging initially but eventually became used to the format (table 4). They reflected the students' sentiments that the laboratories lead them to think critically about their work and made them think like engineers.

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| **Challenge** | • I felt challenged towards the beginning of the semester. However, as the semester progressed, we built a foundation for future lab assignments and could rely on what we were learning in lecture and lab to complete the assignments successfully (and more easily).<br>• Designing the circuits in the beginning was extremely difficult as not enough guidance was given. However, by the end of the semester I did learn how to do it and feel as though I've learned a good amount<br>• It could be difficult to debug the circuit when everyone had different circuits. However, this enhanced the learning process<br>• Overall, this lab was quite challenging, but I do feel that I grew by leaps and bounds in my knowledge of circuitry |
| **Preparation** | • I enjoyed having to come up with the procedure ahead of lab. It allowed us to focus on learning outside of class and practicing/debugging inside of class, much like the flipped-classroom lecture approach<br>• Very challenging but challenges us to think more like an engineer<br>• I think coming up with our own experimental design and procedure allowed us to better understand what we are actually doing in lab |
| **Compared to traditional labs** | • I liked the way lab was set up, it helped to learn a lot more about the different circuits and topics<br>• Was much more work intensive than previous lab sections, but ultimately more valuable to understanding<br>• The class prepares us to think in this fashion. As long as you keep up with the course material, you are prepared for this lab structure<br>• This is the most "hands-off" lab I've been in, which I've enjoyed … most classes do not allow students to problem-solve and think critically about laboratory assignments… |

Table 4: Selected student comments about the design-focused laboratories

**Discussion:**

Design-focused laboratories and projects increase the emphasis placed on the students preparation before laboratories as shown by the amount of time reported by the students for preparation and for post-lab reporting. In such conditions, it is essential that the grading system reflects the amount of effort and ingenuity required by each exercise. We used 50% of the total for the preparation and 30% for the reporting. Other comparable proportions could be used depending on the anticipated effort demanded by each exercise. We also asked the students to prepare the preparatory report and post-lab report with the partner with whom they worked in the laboratory room to encourage collaboration and reduce the workload.

Design-focused laboratories place increase demand for time and effort on the teaching assistants who review the preparation reports submitted by the students and supervise the students during the laboratory experimentation. For our laboratories, the students submitted their reports electronically 48 hours before the experimental sessions to give time to the teaching assistants to review the students' designs and calculations, identify common errors and provide feedback to the students before the experimental sessions. Different student pairs submit different designs, both correct and incorrect designs, that the teaching assistants must assess for correctness before the laboratories while allowing for differences in parameter values and circuit configurations. The teaching assistants are required to complete all the laboratories and projects before the students so they have one validated design in mind and can anticipate common errors in the students measurements and validation tests. When possible, we try to the same teaching assistants for more than one offering of the course so they can be more experienced with the assignments and with the format of the laboratory. In most cases, the primary instructor attends all the laboratories and moderates the initial discussion with the students. The importance of properly training the teaching assistants for open-ended active learning laboratories has been described in the context of science laboratories that use the inquiry-based format [5], [6]. Similar practices must be extended to design-focused laboratories to optimize the students and teaching assistants experiences.

Two four-week projects comprised the majority of the laboratory sessions. To help the students navigate through the projects, specific portions of the overall design and well-defined goals were assigned to each week's work. Laboratory projects that extend over several weeks enable students to work on more complex and more realistic engineering problems that combine multiple aspects of the course subject matter [2], [3]. The student comments in our survey reflected this positive feature of the multi-week projects. With this structure, it is however more difficult to revisit in a laboratory exercise each course topic covered in the classroom. Before adopting such a structure, instructors must decide what role the laboratory have in their courses, and in particular, if relation between the course theory and the laboratory practice is essential [1]. It may not be possible to address all the course topics in the projects.

Students initially had difficulty with the format of the design-focused laboratories as indicated by the preparation grades (figure 2) and the student comments (table 4). Some students never fully adapted to the approach as hinted in the course evaluations. Students need a period of adaptation after years of exposures to traditional cook-book type laboratories [7]. The initial "self-contained" four laboratories that preceded the projects were meant to address in part this challenge. Yet, most students appeared to adapt to the design-focused format with the proper guidance and to appreciate its benefits by the end of the semester-long course.

**Conclusion:**

Design-focused laboratories help students develop their design skills and prepare them to work as professional engineers by exposing them to professional literature. Students can be eased into this type of laboratory framework by structuring the experiments from simpler to more difficult and by gradually increasing the complexity of the experiments and design challenges. Students report satisfaction with design-focused laboratories which they see as more intellectually challenging than traditional "cook-book" laboratories.

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