Student feedback in inquiry-based laboratories for Medical Electronics course

Dr. Jean-Michel I. Maarek, University of Southern California

Jean-Michel Maarek is professor of engineering practice and director of undergraduate affairs in the Department of Biomedical Engineering at the University of Southern California. His educational interested include engaged learning, student assessment, and innovative laboratory designs

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Abstract

Traditional "follow-the-steps" laboratories associated with many engineering courses have limited learning benefits and poorly prepare students to design or conduct experiments as mandated by ABET criterion 3b. The laboratory section of our junior-level Medical Electronics course was redesigned based on the inquiry-based approach. In this approach, the goal of the experiment is specified, but to a large extent, the students devise the experimental procedures with limited guidance from the instructor. For each assignment of our laboratories, students were tasked to design an electronic circuit or an experiment to characterize an electronic component. Students received primary sources such as application notes and data sheets, as well as a few questions to orient their preparation. However, in contrast to the practice of traditional laboratories, a circuit diagram including component values, or a plan for the experiment including information about the measurements to obtain was not provided. Each laboratory session started with a discussion moderated by the instructor and teaching assistant aimed at establishing a layout for the circuit or a template for the design of the experiment.

Two laboratory sections enrolled 23 and 24 students respectively, who completed six "one-session" laboratories and two mini-projects spread over several weeks (electromyogram amplifier and blood pressure monitor). An anonymous student survey was conducted at the end of the semester to gather student feedback about the inquiry-based format used in these laboratories (22 respondents). Quantitative questions scored on a 1-5 Likert scale indicated the students found the laboratory format challenging (score = 4.5). Students perceived they were not sufficiently prepared (score = 2.5) and that the pre-laboratory assignments were not sufficient to prepare for the laboratories (score = 2.2). They reported spending 4.5 hours on the pre-lab assignment and 5.5 hours on the laboratory report, which they perceived to be much longer than the laboratory work in other courses.

Several questions comprised a comment field. The students' statements were analyzed to identify categories of concepts in the comments. "Unclear expectations" was mentioned most often (18 mentions) indicating that the lack of directions unsettled the students. A few students mentioned that they became used to the format as the semester progressed. "Concern about grading" also appeared often in the students' comments (14 mentions). The students found the laboratories "educational" (11 mentions), "time-consuming" (11 mentions), and they reported that one instructor + one teaching assistant to advise them during the laboratories was "insufficient" (10 mentions).

To help students adapt to the inquiry-based laboratory model, we will include in future offerings additional information about expected products in the form of checklists. A gradual ramping up of the grading scheme will be implemented to allow students to adapt to the new approach. Short "best practices" videos will be presented to teach students breadboard wiring and use of the test equipment. Online questions and answers sessions will be introduced to help students prepare for the laboratories.

Introduction and background

Laboratory courses in engineering have been used to develop experimental skills, learn experimental techniques, become familiar with key pieces of laboratory equipment, document the validity and limitations of theoretical models applied to real systems on the benchtop, and promote creativity in conceiving experiments.

Most traditional engineering laboratory assignments use a “cookbook” or “follow-the-steps” approach, in which students follow detailed instructions and procedures to observe and gather measurement data[1]. With this approach, students may learn how to use laboratory equipment and observe that the course theory is reflected in tangible systems. However, it is questionable that the cookbook approach helps the students develop experimental skills, since they follow instructions systematically with the belief that these instructions lead to the expected results. The instructions are never questioned by the students while experimentalists are usually aware of the limitations of their experimental methods and are constantly striving to develop better methods. When questioned about the instructions, students are often incapable of explaining why the instructions asked them to proceed in a certain way rather than in a different way. In addition, the traditional approach does not promote creativity in the laboratory since students are told what to do in exact detail[2].

Criterion 3b of the accreditation process for engineering programs by the Accreditation Board for Engineering and Technology (ABET) requires that graduates from an accredited engineering program have the ability to design and conduct experiments, as well as to analyze and interpret data. Engineering laboratories in which students follow detailed procedures without deviation are unlikely to impart the ability to design and conduct experiments because the students never experience designing experiments and are being led by prescriptive instructions rather than by a protocol they established on their own. Provided they follow the instructions correctly, the students never fail to get the “expected results” while true experiments fail and unexpected findings are sources of learning and discoveries.

Practicing engineers engage in project reviews where they can discuss the progress of a design or development and provide feedback or suggestions to each other. Similarly, scientists have laboratory meetings in which experiments are discussed and different members of the laboratory help each other think through their data and how to move forward. Participants are agents of their own learning and progress by collectively determining the next course of action[3]. This collaborative aspect of deciding together the way forward is also not part of the traditional engineering laboratory model.

Inquiry-based learning takes place while the students are answering questions and solving problems with the instructor serving as a facilitator rather than in the role of deciding all aspects of what the students will do and what they will learn[4]. This approach has been widely recommended in high school science teaching, to a lesser extent in engineering at the college level, and even less so for laboratory teaching.

We describe the implementation of inquiry-based laboratories in a Medical Electronics course, the feedback we received from the students after the first offering of the laboratories, and modifications we have implemented in the second round of testing this model for laboratory instructions.

Methods

The “Medical Electronics” course at our institution is a 4-unit required course in the curriculum of our Biomedical Engineering undergraduate program with an enrollment of about 50 juniors and seniors. The course presents the analysis and design of analog electronic functions commonly found in measurement systems and medical instruments, as well as the components used to implement these functions in hardware. Students learn about sensing and conditioning with medical transducers, transducer amplifiers and active filters, DC power generation and linear power supplies, signal amplification with bipolar junction transistors and analog amplifiers. The students attend two 80 min lectures and one laboratory session every week. To accommodate the large enrollment, two laboratory sessions were traditionally offered with similar numbers of students in each session.

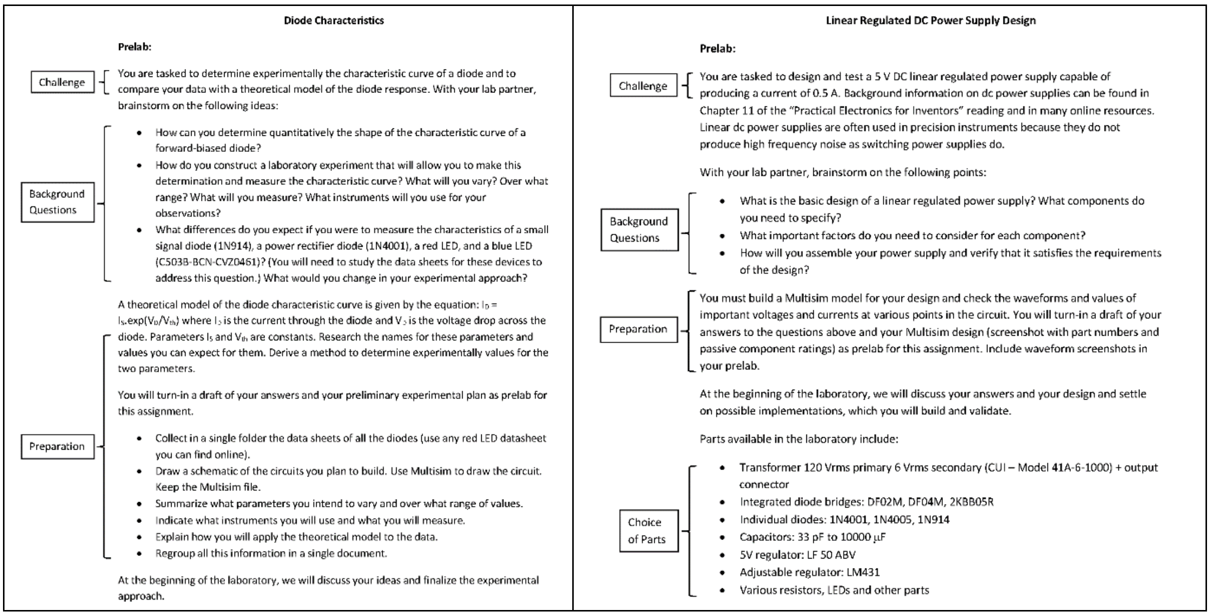
The lecture part of the course is delivered using the flipped classroom instructional approach which promotes learning by collaborative problem-solving[5],[6]. In the classroom, the students work in groups of 4 to 6 to solve problems from an assignment sheet after having viewed at home short recorded video-lectures that present the course material. In-class discussions of circuit analysis and circuit design problems do not follow a pre-arranged order but rather occur at the request of students when they have difficulty understanding the solution to a problem. The active learning student-centered format of the classroom experience contrasted with the traditional “cookbook” format of the laboratories. In addition, the instructor and teaching assistants frequently observed that even if the students could apply specified procedures or perform measurements in a prescribed way for one laboratory, they often would not know when or how to apply the same approach for a different laboratory assignment.

In this context, the laboratory experiments were redesigned in accordance with principles of inquiry-based laboratory instruction[1] in the following manner.

1. Each laboratory assignment was presented to the students as a challenge: an experiment they needed to design and conduct to characterize a component, or a circuit they needed to design and build to accomplish a certain biomedical measurement while complying with specified performance requirements.
2. The assignment did not include procedures to follow. Rather the students needed to conceive and propose their own experimental approach to meet the challenge and characterize the component or complete the design.
3. Each assignment comprised a few background questions to orient the laboratory task in the context of the course content.
4. The students were oriented toward a few primary sources (datasheets, application notes) and encouraged to obtain additional information through web searches without being limited to a unique reference or to the course textbook.
5. When possible, the components and parts that could be used for a design were not limited to a single choice. Rather, the assignment listed a variety of parts the students could choose from. In their laboratory report, they were asked to indicate the reasons for their choices and the information in the components data sheets that lead to the selection.
6. Each laboratory session started with a discussion among students facilitated by the instructor and teaching assistant. The challenge was discussed in the context of the background questions. Procedures were defined with some possibility for deviations. Then the students built the circuitry needed to meet the challenge and collected

experimental data to demonstrate their implementation met the goals of the laboratory. The students summarized their work in a progress report or final report they turned in one week after each laboratory session.

Figure 1 illustrates two examples of assignments that challenge the students to design an experiment to measure the current-voltage characteristic curve for different diodes and to design a linear dc power supply. Each assignment starts by specifying the challenge, which is followed by background questions that the students must research or reflect on in relation to the measurement of the characteristic curve or the basic configuration of a dc power supply. The preparation that the students must complete as a pair is then detailed and often comprises simulations of the circuits and measurements with a circuit simulator (Multisim, National Instruments Corp.). When warranted, a list of parts available in the laboratory supply room is indicated with ample choice for the students to select specific parts for their design.



Diode Characteristics

Prelab:

Challenge — You are tasked to determine experimentally the characteristic curve of a diode and to compare your data with a theoretical model of the diode response. With your lab partner, brainstorm on the following ideas:

Background Questions —

- 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 (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?

Preparation —

A theoretical model of the diode characteristic curve is given by the equation: $I_D = I_S.exp(V_D/V_{th})$ where I_D is the current through the diode and V_D is the voltage drop across the diode. Parameters I_S and V_{th} are constants. Research the names for these parameters and values you can expect for them. Derive a method to determine experimentally values for the two parameters.

You will turn-in a draft of your answers and your preliminary experimental plan as prelab for this assignment.

- Collect in a single folder the data sheets of all the diodes (use any red LED datasheet you can find online).
- Draw a schematic of the circuits you plan to build. Use Multisim to draw the circuit. Keep the Multisim file.
- Summarize what parameters you intend to vary and over what range of values.
- Indicate what instruments you will use and what you will measure.
- Explain how you will apply the theoretical model to the data.
- Regroup all this information in a single document.

At the beginning of the laboratory, we will discuss your ideas and finalize the experimental approach.

Linear Regulated DC Power Supply Design

Prelab:

Challenge — You are tasked to design and test a 5 V DC linear regulated power supply capable of producing a current of 0.5 A. Background information on dc power supplies can be found in Chapter 11 of the "Practical Electronics for Inventors" reading and in many online resources. Linear dc power supplies are often used in precision instruments because they do not produce high frequency noise as switching power supplies do.

With your lab partner, brainstorm on the following points:

Background Questions —

- What is the basic design of a linear regulated power supply? What components do you need to specify?
- What important factors do you need to consider for each component?
- How will you assemble your power supply and verify that it satisfies the requirements of the design?

Preparation — You must build a Multisim model for your design and check the waveforms and values of important voltages and currents at various points in the circuit. You will turn-in a draft of your answers to the questions above and your Multisim design (screenshot with part numbers and passive component ratings) as prelab for this assignment. Include waveform screenshots in your prelab.

At the beginning of the laboratory, we will discuss your answers and your design and settle on possible implementations, which you will build and validate.

Parts available in the laboratory include:

Choice of Parts —

- Transformer 120 Vrms primary 6 Vrms secondary (CUI – Model 41A-6-1000) + output connector
- Integrated diode bridges: DF02M, DF04M, 2KBB05R
- Individual diodes: 1N4001, 1N4005, 1N914
- Capacitors: 33 pF to 10000 μF
- 5V regulator: LF 50 ABV
- Adjustable regulator: LM431
- Various resistors, LEDs and other parts

Figure 1: examples of inquiry-based laboratory assignments. Left panel: design of experiment; right panel: design of electronic circuit to satisfy requirements

The laboratory assignments also indicated what the students needed to include in their laboratory reports to demonstrate they completed the task (not shown). In particular, the assignments asked that the students discuss which information from the data sheets they used as part of their design and testing. Experimental methods however were not specified as part of the assignment.

As noted above, students began the laboratory by a group discussion facilitated by the instructor and teaching assistant. Several students were invited to present at the white board their answers to the background questions and their ideas for completing the task. Data sheets for relevant components were displayed on the projection system and discussed to identify characteristics that justified the choice of the components for the implementation. This discussion lasted about 45 min at the end of which, an outline of the procedures was agreed on. The students spent the rest of the 3-hour lab period building and testing their circuits, as well as gathering measurement data to demonstrate they had met the challenge.

Table 1 lists the topics of the laboratory assignments included in the first offering of the course with the inquiry-based format. One additional laboratory offered at the beginning of the semester presented a tutorial on the software simulator Multisim. Current laboratory experiments as assigned to the students are available at: https://bme.usc.edu/maarek-courses/

Voltage current characteristics of diodes and LEDs	Diode logic design
Design and implementation of a linear regulated dc power supply	Voltage current characteristics of Zener diodes – Zener regulator
Transistor switches	Electromyogram (EMG) amplifier with sound feedback (spread over 3 weeks)
Non-invasive blood pressure pump and measurement (spread over 4 weeks)	

Table 1: list of topics for the laboratory assignments

To assess the students' perceptions of the inquiry-based laboratory format as implemented in the first offering of the course, an anonymous survey was conducted toward the end of the semester. The survey comprised 10 quantitative questions scored on a 1-5 Likert scale, 5 comment fields related to these questions, and 2 questions asking the students to estimate the amount of time they spent working on the preparation and the post-lab report. The quantitative questions were used to assess the students' perceptions relative to their short-term experience in the laboratories and their longer-term perspective on the laboratory learning experience. The students' statements in the comment fields were analyzed to identify recurring themes in the student responses and in this way, extract qualitative feedback to complement the quantitative responses.

Results

The students finished the semester having completed most of the laboratory experiments, even though only a few groups finished the second mini-project dealing the non-invasive blood pressure measurement. During the preparatory discussions, the instructor and teaching assistant noted that some students were reluctant to participate in part because they had not adequately prepared.

Twenty-two students completed the end-of-semester survey out of 47 students enrolled in the course. Figure 2 summarizes the students' responses relative to their perceptions of the inquiry-based laboratories in the short term. On average, the students perceived the laboratories to be very challenging and found that the preparatory assignments were not sufficient to prepare for the benchtop experiments. The students found the initial laboratory discussions and listening to one another during these discussions moderately beneficial. In general, they reported their prior experiences in laboratory classes had not prepared them sufficiently for the inquiry-based approach.

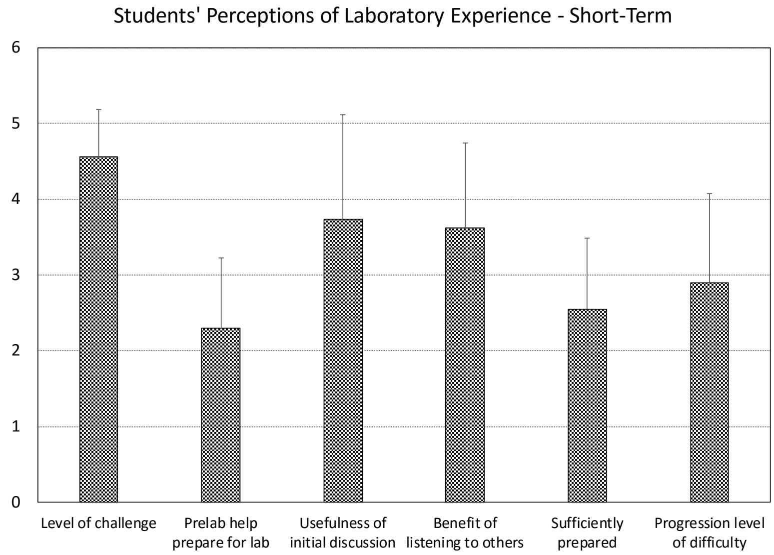


Figure 2 : Students' perceptions – short term

The students were mostly neutral in their assessment of the long-term benefits of the laboratory experience and in the advantages of the inquiry-based format over the traditional "follow-the-steps" cookbook approach (Figure 3). They reported spending on average nearly 5 hours preparing for the laboratories and 5.5 hours to complete the post-laboratory report.

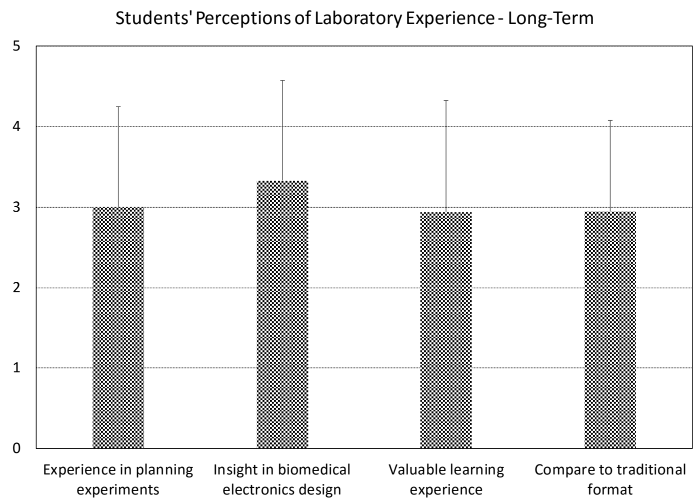


Figure 3 : Students' perceptions – long term

Selected student comments in relation to the level of challenge posed by the lab format and to the contrast with the traditional "follow-the-steps" laboratories are transcribed in table 2. Several students appeared unsettled by the lack of specific directions in the pre-labs and by the amount of time required to prepare for the laboratories. By the end of the semester, many students realized the educational benefits of the approach while remaining ambivalent in relation to the amount of work required by the inquiry-based laboratories when compared to the traditional "follow-the-steps" experiments.

Level of challenge	• I actually liked the challenge involved in the labs and I really preferred it. I just think the grading was too harsh… • A bit hard to work out on own, but makes sense when done in the lab. • The labs were very challenging. While they were related to material learned in class, I spent countless hours researching answers to the specific questions… • Labs are easy with guidance, but require an unreasonable amount of prelab work due to lack of direction. The proper research to complete the prelab can take 2-3 hours… For most of us, this is the first "real" engineering course we take. • The pre-lab assignments were quite hard, I would spend approximately 4-6 hours sometimes on just the pre-lab. Also, they were quite harshly graded. • Post-labs and actual laboratory experiments were difficult, but educational and doable. Whereas the prelab seemed like assignments with vague guidelines that were both confusing and extremely time consuming.
Contrast with follow-the-steps	• We have not had a lab like this before. While we are prepared to design circuits, we have rarely had to design from scratch. • I definitely thought that this method allowed students to explore the topic more and understand what was going on rather than following the steps. • I think it has the potential to be a superior learning experience, and it was definitely more relevant to working in the industry, but it was a pretty sudden change from the traditional lab structure… • More thinking and freedom, more interesting. • As a student with a job and limited time, I would definitely prefer "follow-the-steps" but as a future professional with a career, I feel I learned a lot more with the approach used in our labs. • I would prefer follow the steps laboratories. While I find that I am able to link the labs to the lecture material much better in these labs as opposed to follow the step ones, the labs this year took too much time.

Table 2: Student comments excerpted from survey

Word analysis of the perceptions expressed in the survey revealed that “unclear expectations” was mentioned most often (18 mentions) indicating that the lack of detailed directions in the preparation for the lab and the absence of a pre-determined protocol to follow disconcerted the students. However, a fraction of students indicated they became used to the format as the semester progressed. “Concern about grading” also appeared often in the students’ comments (14 mentions). The students found the laboratories “educational” (11 mentions), “time-consuming” (11 mentions), and they reported that having one instructor and one teaching assistant to advise them during the laboratories was “insufficient” (10 mentions). A lack of preparation and the amount of time passed since the students had their circuits course was also mentioned (5 mentions). This could be related to the fact that, about half the students take the Medical Electronics course as seniors, three semesters after taking the traditional circuits course and its associated laboratory.

Discussion

We redesigned the laboratories of our Medical Electronics course using the inquiry-based approach to promote higher order laboratory skills such as the collaborative aspects of professional laboratory work[1] and the use of primary sources as opposed to textbooks. The inquiry-based laboratories exposed the students to a more realistic laboratory experience when compared to traditional “cookbook” laboratories in that the students had to define the laboratory procedures, choose the parameters they would measure, and choose the parts they would use for their circuit design.

The inquiry-based approach has been used with positive outcomes in several engineering curricula but has often been limited to one or two laboratory experiences[1],[4] as opposed to a whole semester as was done in our trial. There is a novelty aspect to trying the inquiry-based approach on a few occasions which can create buy-in on the part of students. We found mixed results with the inquiry-based laboratories in that the students reported being unsettled by the lack of clear expectations and detailed procedures in the laboratory assignments, which largely reflected their prior experience with traditional laboratory handouts in which all the steps are spelled out. The students were also concerned by the amount of time required to prepare for laboratories for which they had to do research, read technical material written for professional engineers, and find on occasion that they had been on the wrong track. Preparation time for inquiry-based laboratories was also a student concern in other studies[4]. Our students generally had positive impressions of the collaborative aspects of the initial laboratory discussions (Figure 2), which mirrors previously reported results[1].

As a group, our students were neutral in their assessment of the long-term benefits of the inquiry-based laboratories with respect to the insight the approach gave toward planning experiments or toward electronic design as some may do in graduate school or in their engineering careers. Yet, in the free hand comments, a fraction of students expressed understanding the benefits of the approach with respect to the intellectual challenge each experiment represented and how working on these challenges helped their professional development. About half the students taking the course are juniors. We plan to survey them during their senior year to determine if the long term benefits of the laboratory format becomes more salient after additional experiences in classroom or research laboratories.

We did not test the student learning aspects of the laboratories, which could have been done using a laboratory practical exam or inserting questions in the course examinations related to the laboratory experiments. Previous reports indicate that Biomedical Engineering junior students who participated in one inquiry-based physiology laboratory outperformed classmates who engaged in a conventional laboratory experience on exam questions dealing with the topic explored in the laboratory[1]. Likewise, students involved in inquiry-based laboratories in a first-year general chemistry courses obtained higher scores on standard course exams and on laboratory practical exams compared to matched students engaged in traditional follow-the-steps laboratories[2]. They also prepared higher-quality laboratory reports when compared to the students who had the conventional laboratory experience. Thus, there are indications that the inquiry-based laboratories benefit learning the course content through the deeper insights they bring in understanding the material.

Several changes have been implemented in the on-going second offering of the inquiry-based laboratories.

- We added a laboratory section to reduce the number of students in each section to 18 or below. A teaching assistant slot was added to help cover the additional laboratory section which should improve the amount of supervision and guidance the students receive during the experiments.
- We prepared an instructional video to teach the students to assemble more effectively their electronic circuits on the prototype boards and gave them a check list to follow while building their circuits. Another instructional video was prepared to teach the students to read a component data sheet and to find in the data sheet relevant information to help them incorporate the component in their design.
- The first laboratory period was used for a tutorial and review on the use of the laboratory test instruments. Coincidentally, we replaced between the prior offering of

the course and the current offering the traditional self-contained devices (oscilloscope, waveform generator, multimeter, regulated power supply) which many students had not used since their circuits course with a software based all-in one system ("VirtualBench", National Instruments Corp.), which further established the need for the tutorial session.

- Prior to discussing each background question of the laboratory assignments as a large group, we asked the students to discuss the question in small groups for a few minutes. This practice appeared to increase their comfort level in addressing the questions in front of the whole laboratory section. We also incited the students to work in pairs toward their pre-lab by accepting one pre-lab report per pair instead of one per student if they had worked together.
- In grading the pre-lab assignments, more emphasis was placed on the approach presented by the students to decrease their perception of "harsh" grading and increase their self-confidence and motivation.
- The course content discussed in lecture was re-ordered to present integrated devices (operational amplifiers, instrumentation amplifiers, audio and other specialized amplifiers) earlier in the semester. Use of these components is required for multiple laboratories and studying them earlier made the lecture content and laboratories more in tune.

A practical limitation of the inquiry-based approach with respect to electronic circuit design is that the laboratory room needs to be stocked with an abundant choice of parts as the students may select different combinations of components for the same design assignment, which is desirable but also increases the need for supplies. In certain cases, parts availability limited the choices afforded to the students, which also reflected the reality of a professional laboratory. Another practical limitation is linked to student absences. Students who miss a laboratory because of illness, job interviews, or graduate school visits do not participate in the class discussions and find it difficult to complete the laboratory assignment. Last, the format places additional demands on the instructor's time and class management. The instructor must strive to engage all the students in formulating the laboratory procedures. Otherwise, the less-engaged students just follow the procedures designed by the others and fall back in the conventional follow-the-steps approach.

Conclusions

Inquiry-based laboratories offer the promise of developing more creative engineers who can design experiments, utilize professional documentation, and collaborate professionally as engineers and scientists do. We tested a general structure for inquiry-based laboratories and presented some of the benefits and challenges encountered when switching from the traditional follow-the-steps laboratories to the inquiry-based approach. These included a deeper understanding of the course content and of the nature of laboratory work, at the expense of increased time for students' preparation, discomfort in switching from a familiar format to a more abstract format, and the need for additional human and material resources.

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