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Pros and Cons of Laboratory Methods Used in Engineering Education

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Professor Habibi has taught a number of electrical engineering courses such Analog Electronics, Advance Analog Design, Communications, Circuits II, Signals and Systems, and Controls. Professor. Habibi's passion for engineering education, teaching and mentorship is demonstrated each day through his interactions with students inside and outside the classroom. To this point, he has shared his knowledge of best practices in engineering education with his peers through the many articles he has published in ASEE conference proceedings. He has been investigating novel methods on how to motivate students to learn, as well as how to help them become self-directed learners.

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Abstract

Laboratory activities are the most critical part of an engineering education as most students learn by experimenting, observing, and writing reports. Laboratory activities are commonly implemented in curricula using several different instructional methods: the cookbook, design-based, and proposal-based. In the cookbook method, students are provided step-by-step instructions and are required to prototype, experiment, observe, and draw conclusions based on their observations. In the design-based method, students are only provided specifications and must create their own instructions to accomplish the design. In the proposal-based approach, students are required to propose an idea for a project, create their own instruction, and develop experiments to test their design.

In this paper, the pros and cons of each method are discussed. To support the discussion, a survey was conducted using two sections of a design-oriented course as a means for observation. Students enrolled in this course were exposed to each method and their feedback was collected via the survey.

Introduction

Laboratories are an essential part of the educational experience for engineering students. Engineering laboratories are places where students can build, experiment, test, and observe scientific phenomena. Students are able to witness scientific theories come to life; often helping them gain a deeper understanding of the material they are studying [1]. Engineering is a highly practical discipline, thus it is critical that engineering students receive significant experience to be successful in their careers.

The importance of effective laboratory instruction has generally been recognized by the academic community and several notable papers have been published. Feisel and Rosa detailed how the role of engineering instructional laboratories has evolved over history and described some of the challenges facing instructional laboratories as technology has advanced [2,3]. They also presented thirteen fundamental objectives that can be used for the improvement and assessment of laboratory effectiveness and also as guidelines for meaningful research on the topic. Furthermore, the Accreditation Board for Engineering and Technology (ABET) has positively impacted instructional laboratories by defining objectives and expected student outcomes that universities must adhere to in order to receive accreditation [4]. Many of these outcomes can only be achieved in an effective and stimulating laboratory environment, thus instructors must always be improving instructional methods to meet accreditation standards.

While the importance of an effective laboratory experience has been acknowledged by many in the academic community, it has frequently been an under researched topic. Wankat indicated that from 1998 to 2002 only 5.2% of all published articles in the Journal of Engineering Education used laboratory as a keyword [5]. Much of the concentration has been placed on teaching methods and curricula; therefore, interest in laboratory research has become stagnate as a result.

While the authors realize the importance of objectives and assessments to evaluate the effectiveness of instructional laboratories [6], this paper is primarily concerned with the relative advantages and disadvantages of different laboratory methods that can be used to achieve such objectives. Currently, instructors are employing multiple laboratory methods to integrate hands on learning into engineering courses. One of the methods commonly used involves preparing a lab manual, also known as a "cookbook", which includes step-by-step instructions for students to follow. The cookbook method reduces the time required to perform an experiment and is typically less demanding. As a result, students are able to perform more experiments over the course of a semester. On the other hand, the cookbook method lacks self-directed learning opportunities as the problems students face in this method are not open-ended.

A more stimulating option often preferred by instructors is the design-based approach. This approach involves providing students only a set of specifications that their design must meet. This method requires students to create their own lab instruction, work independently, and draw their own conclusions. Through this method students are presented with challenges and are forced to use ingenuity and creativity to arrive at a solution - often leading to a better self-directed learning experience. Due to the difficulty and time required by design-based projects, the number of projects that can be completed in a fifteen-week semester is limited.

An even more involved option, often used by instructors for capstone design projects [7], is the proposal-based method. This method allows students to define a project or problem that interests them, develop methods to arrive at a solution, and compose evidence-based conclusions. Proposal-based projects are often the most memorable for the student because they require the highest involvement; however, they are often dependent on the student's motivation and interest level in which sometimes can be difficult to complete within the time constraints of a semester.

The Electrical Engineering department of the authors' respective university uses a distributed design approach where design projects are integrated virtually in every course. Typically a course will have anywhere from 3 to 7 lab projects throughout the semester. In Analog Electronics classes, labs are mainly design-based and students are responsible for designing, fabricating, and proving that their design meets provided specifications. Many electrical engineering classes also have a final project that is proposal-based. In classes where materials are limited or safety is a concern, lab experiments are cookbook-based and students are responsible for following instructions and describing phenomena observed. To determine the best method, or combination of methods, the effectiveness of each method was tested using two sections of an Analog Electronics course as means for data gathering. Students enrolled in this class were exposed to each type of laboratory approach through various laboratory projects assigned throughout the semester. At the end of the semester a survey was administered and the students' opinion regarding each method was collected and analyzed.

Methods

Course and Lab Project Description

Analog Electronics (EE302) is a course required by Electrical Engineering students at the authors' respective university and is typically taken by students during their junior or senior year. This class is four credits, comprised of three hours of lecture, one hour of discussion and two hours of laboratory instruction per week. The laboratory segment of this class gives students the opportunity to practice theory and learn the operation of commonly used analog devices such as operational amplifiers, diodes, and transistors. Some of the major topics discussed in this class include: diode rectification circuits, transistors, linear amplifiers, etc.

The laboratory segment is typically comprised of five lab projects that are issued throughout the fifteen-week semester. Students are required to complete each project within a three-week time span with deadlines occurring at the end of each week. During the first week, students are required to complete hand calculations and computer based circuit simulations. The second week is dedicated to fabrication and testing of the design, with an instructor evaluation of design performance occurring by the end of the week. Students are then given a third week to write a report discussing the results of the project. Each project description is provided well in advance to the first deadline to ensure students have enough time to become familiar with the project and each project is introduced a week after the related theory is covered in lecture.

For the purpose of this study, five laboratory projects were assigned in fall 2015 with the fourth project being comprised of two parts. The first three projects were design-based, the fifth project was proposal-based, and the fourth project consisted of a design-based part (4A) and a cookbook-based part (4B). This was done to expose students to the three instructional methods discussed in this paper. For the design-based projects students were provided a project description in which the student's university identification number was used to uniquely vary the specifications. An example of design-based project description is shown in Table 1.

Table 1. Example Design-Based Project Description

Design an Amplifier with the Following Specifications	
Student Identification Number	ABCDEFGH
Input Resistance	$\geq$ (10*A) KΩ
Output Resistance	< DE Ω if D $\neq$ 0, Otherwise 50Ω
Voltage Gain	(20 + F) dB
Maximum Voltage Swing	0.1 × F × Power Supply Voltage if F $\neq$ 0, Otherwise F=3

For design-based projects, students were only provided specifications and it was their sole responsibility to complete the design by the due date. Students were graded on the performance of their design using the aforementioned specifications as metrics. The final project was proposal-based and students had the opportunity to research topics covered throughout the semester and define a design that interested them. Students were asked to focus on major topics covered over the course of the semester. They also had to submit a project proposal including a description of the project, specifications, and methods to measure the performance of their design. Proposals were reviewed by the instructor and were either accepted, amended, or rejected. After their proposal had been accepted, students were required to simulate, design, fabricate, and prove the effectiveness and performance of their design. Some of the common proposals included: switching power supplies, audio amplifiers, safety circuits, multi-stage amplifiers, and motor controllers. For many the final project encompassed multiple topics covered throughout the semester and required them to synthesize different pieces of knowledge acquired in the course. Students were also asked to complete a cookbook-based project as an additional part of the fourth lab project. For this segment students were provided a circuit schematic and asked to fabricate, take measurements, and draw conclusions. The cookbook-based lab required no design or simulation.

Survey Instrument and Respondents

An electronic survey was created using the online survey development site, SurveyMonkey.com, then administered to all students enrolled in the Analog Electronics course in fall 2015 after they had been exposed to each laboratory method. The survey instrument was kept direct, brief and was designed so that it could be completed in less than fifteen minutes since no effort was made to select potentially cooperative respondents and no compensation was provided for participation in the survey. The survey included ten questions consisting of a combination of Likert scale and open-ended formats that could be easily summarized statistically without being overly constrained. Some questions allowed multiple selections while others were limited to one selection. The survey also included questions in which respondents were able to rank the lab methods and many questions allowed the opportunity for respondents to provide additional comments. Forty of the fifty-two students enrolled in the two sections of Analog Electronics responded to the survey and their responses were collected anonymously and electronically using SurveyMonkey.com. The survey questions are shown in Table 2 and comments collected by the respondents are shown in Appendix A.

Table 2. Student Survey Questions

<table>
<tr><td>1. What is your interest level in this course?</td><td>• Very interested
• Somewhat interested
• Not interested but I had to take it</td></tr>
<tr><td>2. Out of the three lab types you performed in this class (4A, 4B, and Final Project), which lab did you prefer and would recommend to a friend?</td><td>• Cookbook-based (Lab 4B)
• Design-based (Lab 4A)
• Proposal-based (Final Project)</td></tr>
<tr><td>3. What project/lab type was more challenging?</td><td><table><tr><th></th><th>Not challenging at all</th><th>Slightly challenging</th><th>Moderately challenging</th><th>Very challenging</th><th>Extremely challenging</th></tr><tr><td>Cookbook (4B)</td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>Design-based (4A)</td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>Proposal-based (final project)</td><td></td><td></td><td></td><td></td><td></td></tr></table>Comments:</td></tr>
<tr><td>4. How much time was required to complete each of the projects? (Please enter in numeric form with no letters, i.e. 30 minutes = 0.5)</td><td>• Cookbook-based (Lab 4B)
• Design-based (Lab 4A)
• Proposal-based (Final Project)</td></tr>
<tr><td>5. How well did each project/lab type contribute to your understanding of the course material?</td><td><table><tr><th></th><th>Not well at all</th><th>Slightly well</th><th>Moderately well</th><th>Very well</th><th>Extremely well</th></tr><tr><td>Cookbook (4B)</td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>Design-based (4A)</td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>Proposal-based (final project)</td><td></td><td></td><td></td><td></td><td></td></tr></table></td></tr>
<tr><td>6. Through what project/lab type were you able to retain the most knowledge?</td><td>• Cookbook-based (Lab 4B)
• Design-based (Lab 4A)
• Proposal-based (Final Project)</td></tr>
<tr><td>7. What project/lab, if any, helped you gain skills relevant to your future career?</td><td>• Cookbook-based (Lab 4B)
• Design-based (Lab 4A)
• Proposal-based (Final Project)</td></tr>
<tr><td>8. Which project/lab was the most interesting?</td><td>• Cookbook-based (Lab 4B)
• Design-based (Lab 4A)
• Proposal-based (Final Project)
• None
Comment Box</td></tr>
<tr><td>9. Which project/lab helped you become a better self-directed learner?</td><td>• Cookbook (Lab 4B)
• Design-based (Lab 4A)
• Proposal-based (Final Project)
• None
Comment Box</td></tr>
<tr><td>10. Do you have any comments or recommendations that could help us improve practical experience for students?</td><td>• Comment Box</td></tr>
</table>

Results

Were the students interested in the course? According to the survey results (shown in Figure 1), the majority of students were somewhat to very interested in the course. Analog Electronics is a course required by the electrical engineering department and is a prerequisite for numerous senior-level design courses. As such, students understand that learning the concepts covered in Analog Electronics is critical to their education and career. Considering the survey results shown in Figure 1 and selected comments shown in Appendix A, it was determined that the majority of students took the survey seriously.

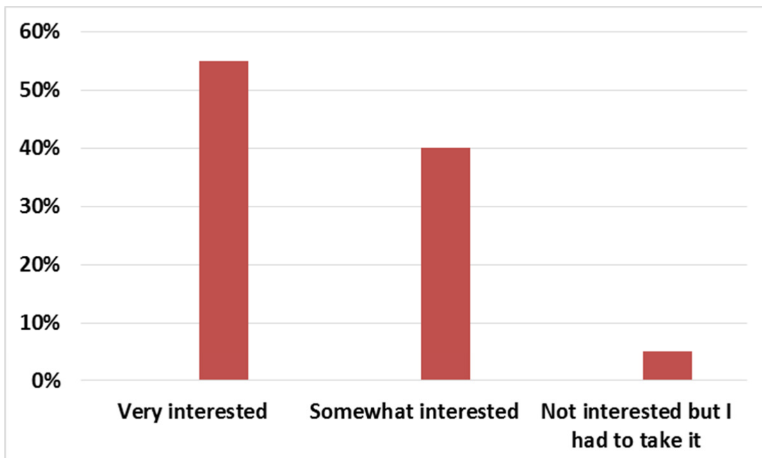

Figure 1. Students' interest in Analog Electronics versus percent of respondents

What method was preferred and what method would students recommend to a friend? Based on the survey results (Figure 2), 47 percent of the students preferred the design-based method, 35 percent preferred the proposal-based method, and 17 percent preferred the cookbook method. The students were also asked what method they considered to be the most challenging and the results are shown in Figure 3. Interestingly, despite being the easiest method, the cookbook-method was significantly less preferred indicating that students prefer to be challenged. The results confirm that even though the design-based and proposal-based methods are more challenging, they are preferred.

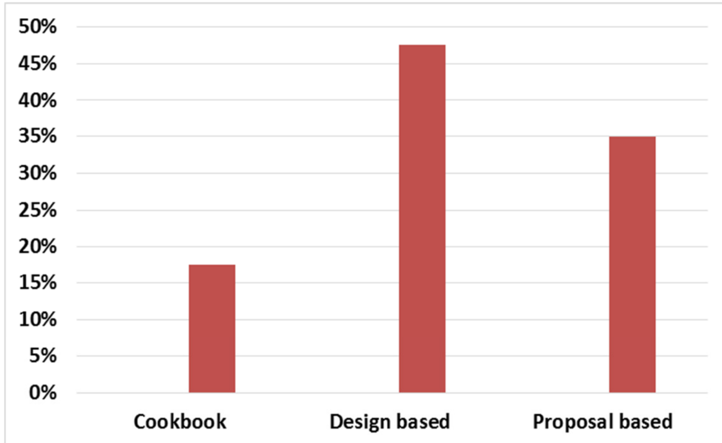

Figure 2. Students' preference toward lab methods

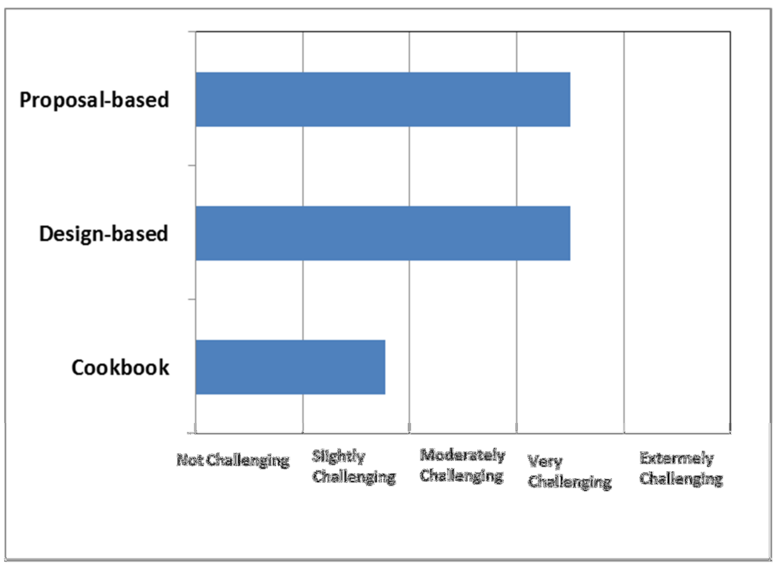

Figure 3. Students' perception of how challenging each lab method was

How much time was required to complete each of these labs? As can be expected, the responses to this survey question were quite varied. The average time required to complete the cookbook-based lab project was 2.0 hours, design-based 9.0 hours, and proposal-based 17.0 hours (Figure 4). The proposal-based project had the highest standard deviation at 11.5 hours indicating that the difficulty of proposal-based projects varied based on the project chosen by the student, their interest level, motivation, and how well they understood the applicable topics.

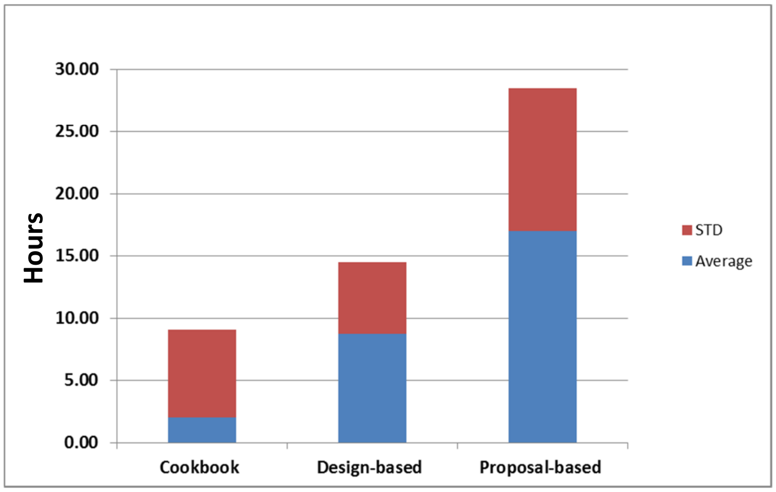

Figure 4.Time required to complete each project

Which method helped students become better self-directed learners? According to the survey results, more than 85 percent of students selected the proposal-based method as the best at improving their self-directed learning. One of the student outcomes that the ABET expects a graduate to acquire is "a recognition of the need for, and an ability to engage in life-long learning" [4]. This recognition cannot occur unless students are given the opportunity to become self-directed learners. While proposal-based projects are both challenging and time consuming for the instructor and students, their ability to stimulate life-long learning renders them essential to a well-balanced laboratory experience.

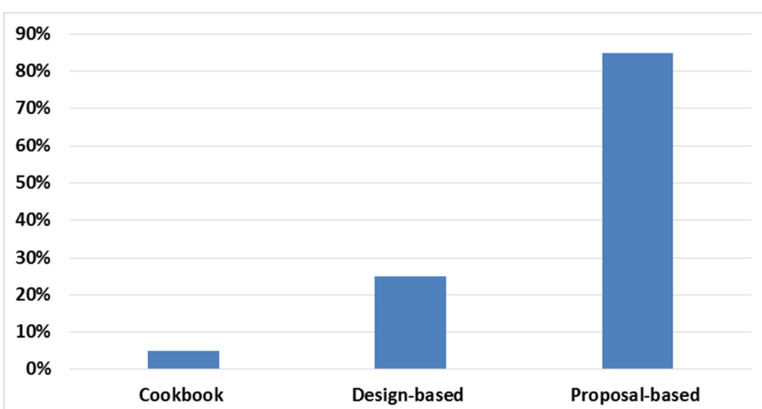

Figure 5. Students' response to which project helped them become better self-directed learners

What method best contributed to the students understanding of the course material and their ability to retain the most knowledge? Understanding and retaining knowledge are directly related; students remember concepts longer when they understand them deeper. As indicated by the survey results (Figures 6 and 7), students were able to understand the material better and retain more knowledge through the design-based and proposal-based projects. Both these projects required more time and effort to learn the concepts needed to arrive at a solution; therefore, the students were able to retain more knowledge completing these projects than they did completing the easier cookbook project.

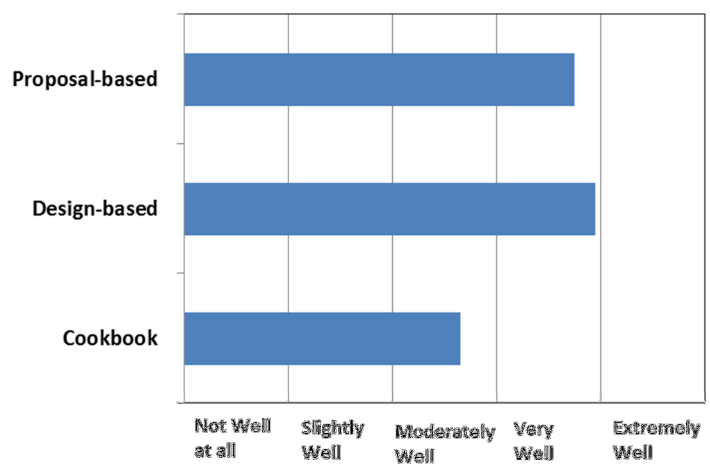

Figure 6. Contribution of each method to the students understanding of the course material

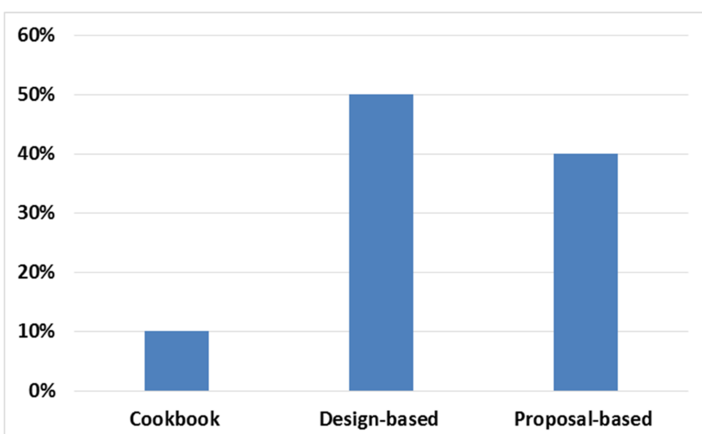

Figure 7. Method through which students were able to retain the most knowledge

What method best helped students develop skills relevant to their future careers and what method was most interesting? Not surprisingly the results for each of these questions were very similar; students are generally more interested in projects that they believe will help them develop skills they can use in their future careers. Figures 8 indicates that students believed the proposal-based project offered the most benefit to their future while the cookbook project offered little to no benefit to their future careers. While more than thirty percent of students stated that the design-based method will help them transition into the workforce, seventy percent believed that the proposal-based method will help facilitate their transition to industry and strongly influence their future careers. Students also specify that proposal-based project was the most interesting one among others (Figure 9).

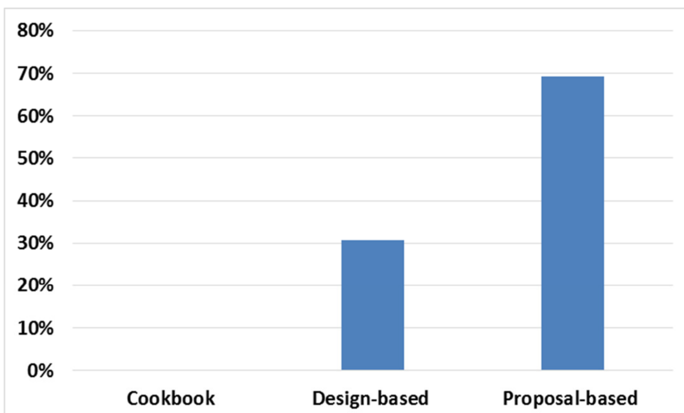

Figure 8. What method best helped you develop skills relevant to your future career?

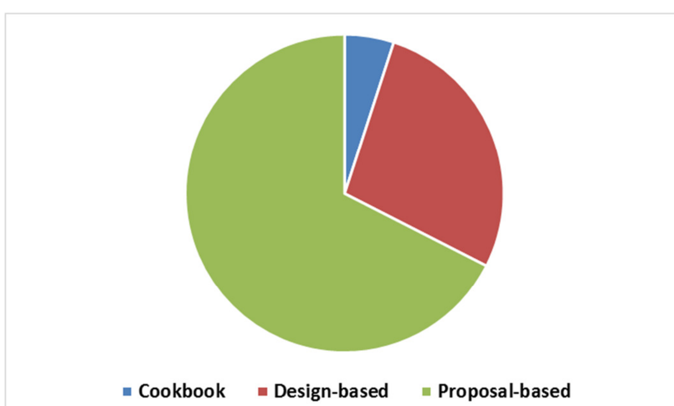

Figure 9. What method was the most interesting?

Conclusion

Both past research and the results of this experiment show that cookbook labs lack the ability to provide students a self-directed learning experience [8,9]. The simplicity of the cookbook method prevents students from being able to think critically and turn observations into knowledge. Step-by-step instructions provided in a cookbook lab are structured so students can complete a lab in a timely manner without encountering any problems. Subsequently, students are not sufficiently challenged and are isolated from problem-solving opportunities that improve self-directed learning. Despite these disadvantages, the cookbook method is still widely used by instructors as the sole method of laboratory instruction in their classes. While this method does have many disadvantages, and should not be used as the sole method of laboratory instruction, there are instances in which it can be useful. Because of their straightforwardness, cookbook projects can be used when students have not yet learned enough material, or when there is not enough time to complete a design or proposal based project. These projects are not only less time consuming for the students but also for the instructors. Cookbook projects are also useful when safety is a concern, when equipment can be damaged, or when students cannot provide their own materials.

While the design-based method offers many advantages, which the cookbook method does not, it is also not recommended as the sole method of laboratory instruction. The design-based method was created to improve self-directed learning in the laboratory as this type of learning often yields greater retention and deeper understanding. Through design-based projects students are able to think creatively, solve open-ended problems, and develop skills relevant to their future careers. Design projects have been shown to improve understanding and increase material retention, and are also preferred by students. Although the design-based approach may seem like an ideal method for laboratory instruction, it itself also has disadvantages. Because design projects are more demanding, instructors are often limited to assigning five to seven of them per fifteen-week semester, compared to fourteen to fifteen cookbook projects for the same duration. Design projects also risk causing frustration amongst students, and this frustration can lead to decreased motivation and interest in the material.

Finally, the proposal-method goes beyond what the design-based method offers in self-directed learning experience, and provides the best opportunity for students to gain skills relevant to their future career. Because the proposal-based method is so open-ended, students have the opportunity to investigate topics that interest them. Consequently, proposal-based projects are often the most memorable for the student. The benefits of the proposal-based method are not without consequences, however. Because of the difficulty associated with these projects, many students elect to choose a simple project they can easily complete. Other students may choose to duplicate a project that was completed in the past by one of their peers, or may use the Internet to find detailed instructions.

Proposal-based projects are often assigned toward the end of the semester when students are overwhelmed by projects and finals in other classes. Proposal projects often vary greatly based on the motivation and interest level of the student and this presents challenges for the instructor. It is the instructor's job to review each proposal in detail and make necessary adjustments. Additionally, proposal-based projects are not easily assessed. Due to the variety, these projects do not easily lend themselves to systematic grading. While many students are able to complete their project, it is not always certain how much they have learned. Thus instructors must use effective assessment methods to ensure students understand their designs in detail. Because of this the proposal-method demands highly experienced instructors. For these reasons the proposal-method is not always suitable for freshman and sophomore level undergraduate courses. It should however be an option for junior and senior level undergraduate courses where students have sufficient background in a topic and also have a higher level of motivation.

Results of the experiment indicated that each method has its own advantages and disadvantages, and no method can become the sole solution for an effective laboratory experience.

In conclusion, the authors suggest that a combination of all three lab methods be used during a semester for a junior/senior level course. Students can be introduced to material by completing a cookbook project and can work into three to four design-based projects. At the end of the semester a proposal-based project can be used to encapsulate material learned throughout the course and provide students with a memorable experience.

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Appendix A – Selected Student Comments

"I like the cookbook but I learn much more with the design-based. The design-based takes a lot more time"
"Cookbook method does not offer much insight on how circuit worked. Design-based really taps into the inner working of the design as well as the troubleshooting aspect which helps clarify concepts. Open ended proposal-based is to open. I really struggled with mine."
"What made the design project more challenging and more enjoyable was the challenge of accounting for the various parameters of each component you have selected"
"The more you struggle, the more you are forced to learn. Time consumption for final projects is a lot and I always seem to struggle with them. I have come to really enjoy this class. I like the cookbook labs but I get way more out of a design lab. I like the getting the cookbook lab done with fast and out of the way. I don't care for the difficulty of design lab but when I am finished with it, I appreciate it more."
"I feel like I learned the most about the project I was working on through the final project."
"The design-based I found very challenging but the direction helped push my limits. On the proposal-based I found something within my limits reducing the amount of learning"
"The time commitment for design-based was very high, possibly a mix of cookbook and design to find a happy medium."
"The cookbook labs do show an application of the information we learned in class, but the design-based labs forced me to think much more deeply about the topics we covered. The operational amplifier and diode labs my not require the more in-depth approach because they seemed to be more like setup for the BJTs and MOSFETs. The BJT and MOSFET amplifiers, on the other hand, do need the extra work to fully grasp the concepts of the class."
"The cookbook lab was refreshing due to having strict goals/methods to complete the work, making it less stressful. All in all the design/proposal-based labs probably forced this student to learn more but when lacking some instructions for steps i.e. b2spice methods, it was more difficult to complete the labs in a timely fashion."
"I thought the labs were done very well. You gave us just enough to make the labs challenging but not impossible. They were given to us at a good rate and not overwhelming. I loved doing the labs and was probably my favorite part about the course."
"Continue with design and proposal-based labs. Even though they take much longer, you learn a lot more by designing and troubleshooting"
"Learning involves examples, observations, and adjustments. The cookbook was great because it gave a real example of a functional circuit. The design in 4A takes it the next level (although the cook book should have been completed prior for best results). The final design was wide open and, in some cases, part dependent and can have a counter effect on the learning from this course."
"The most frustrating part of design or proposal-based labs are how much time must be spent on them. Although this is why you learn so much from them it can make the class very frustrating with the assigned homework, and quizzes to do as well."
"I personally learned the most from the projects that gave specific specifications than from the final project. From those labs I was able to gain the basic knowledge behind each amplifier/rectifier that was required to be designed."
"I would suggest doing more cookie cutter labs but keep the same amount of design labs. Cookie cutter labs can be finished in little to no time and if a student does bad on one design lab the cookie cutter labs can help the grade out. Also cookie cutter labs can cover topics that were not covered on the test or design labs, such as common base/gate circuits"
"It is difficult to compare the benefits of design-based labs to proposal-based when the final project was during the busiest time of the semester. If this was my only class I would have dived into my project more. I believe most students choose a project that they could get done so that they wouldn't get trapped trying to salvage a failed project".
"I liked the way the practical experience was set-up. It would be nice if there was more time between labs, but then again this is EE3020 so the name itself entails a lot of work."
"At times I found YouTube videos that explained concepts from the lab material in two minutes when a 50 minute lecture could not perform the same function. The design-based circuit is a substantial investment in time, I found dealing with new material and designing a circuit based off it a difficult mix. Perhaps a cookbook lab to promote better understanding coupled with a design lab a week late once material comprehension is better."